Aspect consulting
IN-DEPTH PERSPECTIVE

ARSENIC ISSUES EVALUATION
Des Moines Creek Regional Detention/Retention Facility
Prepared for: Des Moines Creek Basin Committee

Project No. 030185-001-03 • April 14, 2004

Aspect Consulting, LLC

In Association with:

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Des Moines Creek Basin Committee

APR 21 2004

April 14, 2004

Ann Kenny
Department of Ecology
3190 160th Avenue, SE
Bellevue, WA 98008-5452

Dear Ms. Kenny:

The Des Moines Creek Basin Committee is pleased to forward, for your consideration, additional information to assist in your consideration of our request for a Water Quality Certificate for the Des Moines Creek Restoration Projects.

Attached please find five (5) copies of the Arsenic Issues Evaluation for the Des Moines Creek Regional Detention Facility. The Arsenic Issues Evaluation documents the arsenic issues evaluated and discussed at a meeting between Basin Committee representatives and the Department of Ecology on January 29th, 2004.

The report provides a description of the environmental setting, summarizes the key components of the project, identifies the principle project related environmental changes that could influence arsenic releases, summarizes existing data, provides a discussion of potential project-related arsenic release mechanisms, identifies a number of project modifications that could address potential arsenic releases and describes proposed project monitoring programs.

Should you have any questions please feel free to call me at 206-354-9749 and I would be happy to put you in touch with the appropriate member of our technical team.

Sincerely,

David Masters,
Project Coordinator

cc: Des Moines Creek Basin Committee

Contents

List of Figures

List of Appendices

1 Executive Summary

The Des Moines Creek Basin Committee has designed a suite of projects intended to aid in the protection and restoration of the 3.5-mile-long Des Moines Creek System. The Des Moines Creek Regional Detention/Retention Facility (RDF) is one of the major components of this suite of projects. It is designed to attenuate peak flows by enhancing storage capacity in the vicinity of the Northwest Ponds, located on and near the Tyee Golf Course south to southwest of the Seattle-Tacoma International Airport.

Construction of the RDF will necessitate large-scale excavation of soil that will need to be exported or otherwise used on the site. During the design phase of the project an environmental soil sampling program was completed by King County to evaluate disposal and end-use options for the excavated material. Elevated levels of arsenic were measured in the proposed excavation areas with concentrations increasing with depth. Concerns were raised in regards to arsenic impacts on the RDF project by Ecology representatives during the permitting process associated with a 401 Water Quality Certification (WQC).

The Basin Committee commissioned an analysis to predict how the proposed RDF project would affect arsenic levels in the environment resulting from the project construction and operation. Potential project design modifications and monitoring programs were proposed to allow reasonable assurance that the project could be constructed without causing long-term impact to surface water quality. The Basin Committee representatives presented their finding to Ecology permitting authorities on January 29, 2004. This report documents the arsenic issues evaluated and discussed at the Ecology presentation and is in support of the request for 401 WQC.

The environmental setting of the project area is documented to develop a conceptual understanding of the geology, groundwater, surface water and land use/development in the project area. The RDF project, including project objectives, construction sequence and operation, is described. Environmental changes associated with the RDF project are evaluated, and are supplemented by existing data that have been historically collected in the project area.

A conceptual model describing arsenic mobility is developed based on integration of available site data and comparison to published models for arsenic biogeochemical cycling in similar environments. The potential for arsenic impacts resulting from the RDF project and site-specific conditions is evaluated. Potential project design modifications are developed to reduce and prevent the release of arsenic during construction and operation of the RDF.

A monitoring program is described to establish pre-construction conditions, monitor potential impacts during construction and provide a monitoring system to ensure long term operation of the facility does not impact surface water quality.

2 Introduction

2.1 RDF Project and Arsenic

Des Moines Creek, approximately 3.5 miles long, has a drainage basin of about 5.8 square miles in western King County, Washington and discharges to Puget Sound southwest of SeaTac International Airport. The basin planning projects will enhance the current conditions of hydrology, erosion and channel stability, and biological habitat of Des Moines Creek. The Des Moines Creek Basin Committee, an interjurisdictional forum including King County, the City of SeaTac, the City of Des Moines, the Port of Seattle, and the Washington State Department of Transportation, has worked cooperatively for a number of years on a basin planning project (Des Moines Creek Basin Committee 1997).

One of the major components of the basin planning effort is the construction of the RDF, which is further described in Section 2.2. Figure 1 presents a *Site Location Map* which shows the layout of Des Moines Creek and major elements of the RDF project. During the design phase of the project, elevated levels of arsenic were measured in organic rich soil (peat horizons) within the proposed excavation area for expansion of the RDF. This finding has delayed the permitting of the RDF facility and may result in the need for implementation of project modifications to protect the water resources of Des Moines Creek.

The source of the arsenic has not been determined as a result of this evaluation. However, distribution of arsenic at the site does not suggest deposition of airborne ASARCO contamination as a direct source, and there are no reported arsenic generating operations or activities associated with airport operations. Potential sources likely include historical agricultural use of herbicides and pesticides on former farm and orchard land in the surrounding area.

Construction and post-construction operations of the RDF have the potential to change the existing hydrology and geochemical conditions and could result in mobilization and transport of arsenic. Project design modifications are proposed (contingent on testing and data collected during future monitoring programs) to allow reasonable assurance that arsenic levels remaining at the site will not impact surface water quality.

This report describes the RDF project, existing conditions and, the potential impact of the project on existing conditions. Project modifications are proposed which can be implemented to prevent and/or mitigate impacts, as necessary. A detailed monitoring program is proposed to measure background, baseline, construction and post-construction levels of arsenic at the project area.

2.2 RDF Project

Over time, urban development of the Des Moines Creek watershed has resulted in increased stream flows and channel erosion in the creek, limiting suitable fish habitat. Existing land use plans indicate increasing urbanization of the watershed will occur in the future. A RDF to temporarily store excess runoff and reduce downstream impacts has been identified by the Basin Committee as one among several projects to improve conditions in Des Moines Creek. The RDF will be constructed in the upper reach of the West Fork of Des Moines Creek, near the Northwest Ponds--an open water body in an surrounding wetlands area--and Tyee Golf Course, south/southwest of Seattle-Tacoma International Airport. The RDF project works in conjunction with several other projects. A flow bypass will be constructed to route a portion of stream flows in the East Fork of Des Moines Creek directly to Puget Sound, reducing instream flows during storm events. A diversion pipe will also route portions of East Fork stream flows that exceed the capacity of the bypass pipeline to the RDF impoundment area for controlled release to Des Moines Creek. The single RDF will thus serve both major tributaries of Des Moines Creek. A new, higher capacity channel will also be constructed for the West Fork of Des Moines Creek. In addition to improving conditions in Des Moines Creek, the overall RDF project will also reduce flooding and open water areas at the golf course directly south of the airport runways, which will reduce potential risks to airplanes from bird impacts consistent with Federal Aviation Administration (FAA) requirements.

Substantial soil excavations adjacent to the Northwest Ponds, behind the constructed impoundment berm, are planned as part of the RDF project to increase storage capacity. During the second half of 2003, King County, acting in the role of technical consultant to the Des Moines Creek Basin Committee collected and analyzed soil samples from the planned soil excavation areas to provide information for excavated soil management and disposal decisions. Elevated arsenic levels were found, with concentrations up to 432 milligram/kilogram (mg/kg) (dry weight basis). Most of the sampled borings had an "inverted" depth profile, with arsenic concentrations increasing with depth. These results indicated a potential for elevated arsenic levels in post-excavation, near-surface soils at the RDF. They also raised the possibility that construction and operation of the RDF project as proposed could result in mobilization and transport of arsenic. Arsenic was thus identified as a potential concern only shortly before the planned start of construction in 2004.

A detailed analysis identifying the arsenic source was not performed as part of this evaluation. Potential project design modifications (see Section 8) could be implemented as necessary during the construction and post-construction period and provide a the necessary level of protection to surface water quality without the full understanding of the arsenic source. However limited research conducted for this evaluation regarding the source of arsenic in the project area indicates the following:

- There are no reported arsenic generating operations or activities at the airport.
- The arsenic concentrations observed in soil at the RDF increased with depth which conflicts with typical ASARCO smelter profiles.
- Volcanic ash layers observed in the peat soils at the RDF project area contained low levels of arsenic.

- Former land use practices in the upper West Fork basin and within the RDF project area consisted of agricultural use which may have resulted in the use of arsenic laden herbicides and pesticides.
- Elevated levels of arsenic measured at the RDF project area typically occurred in organic rich peat soil horizons.

In the context of obtaining a 401 WQC, Des Moines Creek Basin Committee representatives met with the Washington State Department of Ecology (Ecology) in December 2003 to present and discuss these sampling results for arsenic. Additional evaluations were then performed by a consultant team on behalf of the Basin Committee based on the RDF project description and initial soil sampling results. A conceptual model was developed to provide a framework for considering possible arsenic releases associated with the RDF project. A number of project modifications were identified for review, and several types of sampling programs were designed as part of this effort to assess arsenic issues. Sampling programs were developed both to support further project design (for prevention/mitigation of possible project-related arsenic releases) and to provide environmental monitoring to identify project impacts. Basin Committee representatives and the consultant team met with Ecology on January 29, 2004 and orally presented their evaluations and proposed sampling programs. Handout packages summarizing the presentation were provided at the meeting. This report provides a more detailed discussion of the evaluations of arsenic issues.

A separate Sampling and Analysis Plan (SAP) has been developed for the proposed sampling programs. The SAP identifies sampling locations and provides detailed discussions of sample collection and laboratory analysis protocols, and also includes a Quality Assurance Project Plan (QAPP).

The Des Moines Creek RDF Project has been developed over a number of years. While this report is intended to provide sufficient information to understand the evaluations of arsenic issues and proposals for project modifications and sampling programs, the reader interested in greater detail should consult the historical series of project reports (see References, Section 10).

2.3 Report Purpose

This report documents arsenic issues associated with the RDF project and provides project modifications (to be implemented as necessary) and monitoring programs as were presented to Ecology by Des Moines Creek Basin Committee representatives at the January 2004 meeting. The report serves as the basis for establishing reasonable assurance that the RDF project and proposed project modifications and monitoring programs will not cause adverse harm to surface water quality. The report supports the issuance of the 401 WQC for the RDF project[1].

[1] The presentation of site conditions in this report will also provide the basis for any appropriate MTCA activities, which will be conducted and reported independently of this document and the 401 WQC process.

The report provides a technical environmental review of existing site conditions, develops a conceptual model in regards to arsenic transport and mobility under existing conditions and construction of the RDF project and proposes project design modifications which will provide reasonable assurance that the RDF project will not increase further impacts to surface water quality. The conceptual model and the data used to develop the model presented in this report are the foundation for the work of the Des Moines Creek Basin Committee to:

- Discuss the construction project;
- Identify potential impacts and changes associated with the project;
- Assess alternatives for preventing/minimizing/mitigating adverse impacts during construction;
- Design data collection and evaluation processes to monitor impacts;
- Select construction design modifications based on site specific data and properties; and,
- Discuss long term monitoring to assess the prevention/minimization/mitigation success.

2.4 Report Organization

The major sections of this report are as follows:

- **Section 3, ENVIRONMENTAL SETTING:** provides a description of environmental conditions near the RDF project location and their effects on potential arsenic pathways.
- **Section 4, RDF PROJECT DESCRIPTION:** provides a summary of key components of the RDF project as proposed, prior to any added mitigation measures.
- **Section 5, ENVIRONMENTAL CHANGES ASSOCIATED WITH RDF PROJECT:** identifies the principal project-related environmental changes that could influence arsenic releases.
- **Section 6, EXISTING DATA:** summarizes the available arsenic data, and related chemical information, in the project vicinity and identifies related sampling programs.
- **Section 7, CONCEPTUAL MODEL FOR ARSENIC MOBILITY:** provides a discussion of arsenic environmental cycling and potential project-related arsenic release mechanisms.
- **Section 8, POTENTIAL PROJECT DESIGN MODIFICATIONS:** identifies a number of project modifications that could address any potential project-related arsenic releases.

- **Section 9, PROPOSED MONITORING PROGRAMS AND OBJECTIVES:** describes pre-construction, construction, and post-construction monitoring programs for arsenic impacts as well as a more extensive baseline monitoring program to characterize arsenic environmental cycling in the project area.
- **APPENDIX A** contains a description of the geologic unit distribution within the project area, and **APPENDIX B** presents supporting information regarding the geochemistry of arsenic.

3 Environmental Setting

3.1 Des Moines Creek Basin Description

The Des Moines Creek basin consists of an urbanized watershed that covers 5.8 square miles in the Seattle-Tacoma metropolitan area. Des Moines Creek is approximately 3.5 miles long and discharges to Puget Sound at the Des Moines Creek Beach Park. The creek originates on a low-gradient upland plain near the south end of the Seattle-Tacoma International Airport. Two main tributary branches, the East and West Fork, converge at the Tyee Golf Course at river mile (RM) 2.35. The East Fork flows out of Bow Lake and is channeled through a series of subsurface pipes until it surfaces near 26th Avenue South. The West Fork flows out of the Northwest Ponds located to the northwest of the Tyee Golf Course. The creek descends steeply through a ravine located south of South 200th Street and is thought to follow former glacial-age outwash channels to Puget Sound (Booth, 1996). The portion of the RDF project impacted by the arsenic levels in soil is located near the Northwest Ponds and along the West Fork of Des Moines Creek.

3.2 Geology

Subsurface soil and geology conditions in the vicinity of the RDF were evaluated based on a review of existing boring and well completions within an approximate ¼-mile radius of the project area. Existing environmental and geotechnical soil borings and water supply wells completed in the project area are presented on Figure 2. Geologic cross section profiles are presented in Figure 3 through 5. The cross section presented in Figure 3 extends from the Port's Lagoon 3 area through the proposed RDF project area to deep water supply wells completed near the southeast area of the Tyee Golf Course. Figure 4 and Figure 5 show an enlarged view of the RDF area depicting existing and constructed ground surface, respectively. Select arsenic levels measured during previous investigations (see Section 6.3) are indicated on the detailed cross sections. Geologic profiles have been constructed using exploration logs generated during geotechnical and environmental investigations conducted at the site as well as previous investigations completed in the project area (AESI, 2000; Booth, 1996; King County, 2003h and 2003i, Parametrix, 2003; Robinson & Noble, 2001; Sitka Corp, 1999; Sitka Corp., 2002) and well logs on file with Ecology.

The geologic history of the Puget Sound Basin and the study area has been dominated by repeated glacial and non-glacial cycles of deposition. Sedimentary deposits associated with up to four of these cycles have been identified in the Des Moines Drift Plain. The most recent glaciation in the project area occurred during the Vashon Stade of the Fraser Glaciation. Deposits from this glaciation are commonly identified with a "Vashon" or "Qv" prefix. All sediments deposited prior to the Vashon Stade, including both glacial and non-glacial deposits, are identified with a "Pre-Fraser" or "Qpf" prefix. The following section outlines the stratigraphic division of these soil units and a description of each soil type. The interpreted spatial distribution of each unit is presented in Appendix A.

3.2.1 Stratigraphy and Soil Units

An idealized stratigraphic sequence for the study area (starting with the onset of a glacial cycle) would consist, from the bottom up, of the following deposits:

- **Pre-Fraser glacial and non-glacial deposits.** These deposits are differentiated as either coarse-grained (primarily sands and gravels) or fine-grained (dominated by silts and clays).
- **Glacio-lacustrine Transition Beds.** The beds consist of fine sands, silts, and clays that were deposited in a lake impounded by the advancing glacier. These sediments mark the change from a non-glacial depositional environment (much like the Puget Sound region today) to a glacially dominated environment. Some non-glacial fine sediments can also be included in this unit.
- **Advance Glacial Outwash.** These outwash sediments are deposited by meltwater streams flowing from the margin of an advancing glacier and consist of fine to medium sand, and sand and gravel.
- **Glacial Till.** Till is deposited at the base of a moving glacier and consists of an unsorted to poorly stratified mixture of clays, silts, sands, and gravels.
- **Recessional Glacial Outwash.** These soils were deposited by meltwater streams issuing from a receding glacier and consist of silty sands, sands, and sands/gravels.
- **Interglacial, or non-glacial, sediments.** These chronologically recent (Holocene) sediments consist of interbedded clays, silts, sands and gravels, and peats. The interglacial environment was characterized by erosion in stream channels and of upland areas, as well as soil deposition in low-lying areas.
- **Fill.** This category includes soils that have been imported or rearranged by anthropogenic activities.

Typically, some or all of the deposits of an idealized sequence are missing in any area due to non-deposition or erosion between successive deposits.

The unit of particular significance related to the RDF project is the organic rich peat soils observed in the Cell 1 and Cell 2 excavation areas of the RDF project. Elevated levels of arsenic were measured in the peat soil during soil investigations performed by King County (Section 6.3). The peat appears to be at least 13.5 feet thick near the southern area of Cell 1 and is present through-out the proposed excavation areas as observed in Figure 6.

3.3 Groundwater

The regional groundwater system consists of a series of layered water bearing zones and aquitards that are laterally extensive, but locally discontinuous. The uppermost water-bearing zone is the recent alluvium and recessional outwash deposits which contain perched groundwater. That layer is typically separated from the underlying confined aquifers by the Vashon glacial till or the uppermost pre-Fraser fine-grained deposits. The uppermost confined aquifer is formed by the Vashon advanced glacial outwash deposit (Qva). Transition beds (Qtb or Lawton Clay) or pre-Fraser fine-grained sediments

underlie the advanced outwash and form a discontinuous aquitard that separates the shallow Qva confined aquifer from the underlying pre-Fraser coarse-grained deposits. Where that aquitard is absent, aquifers in the Qva and upper Qpff unit are hydrologically connected. This situation exists in the Des Moines Creek drainage southeast of the Northwest Ponds. Additional alternating layers of pre-Fraser fine and coarse-grained sediments have been regionally identified. The deeper confined aquifers can be hydraulically connected where the separating aquitard (a Qpff unit) is absent. Groundwater in the vicinity of the project area is observed in shallow perched zones and in coarse-grained deposits comprising regional aquifer systems.

3.3.1 Perched Groundwater

Shallow perched groundwater has been observed during several phases of soil sampling completed by KCDNR in the Cell 1 and Cell 2 proposed excavation areas for the RDF. A glacial till has been encountered in several geotechnical borings drilled in the project area and provides a low permeable soil unit which in effect contributes to the perched groundwater condition observed at the site. Perched groundwater was encountered in organic rich wetland soils at depths ranging between 1 to 4 feet below ground surface (bgs) during the August 2003 soil sample event. The corresponding groundwater level elevation ranged between approximately 250 to 243 feet NAVD 88. Figure 7 presents an apparent groundwater gradient for the perched groundwater zone north and east of the Northwest Ponds based on the August 2003 water level encountered during the advancement of the soil borings. The August 2003 data indicate a perched groundwater gradient towards the Northwest Ponds which infers that the RDF project area is part of a shallow groundwater discharge zone where shallow groundwater interflow is discharging directly to the ponds.

Two shallow monitoring wells (HP28-2 and HP28-3, see Figure 2) were installed north of the Northwest Ponds complex as part of a conditional requirement for a Port of Seattle 401 WQC related to Third Runway environmental permitting. The monitoring wells are typically 2.5 feet in-depth and where installed with auguring techniques (Parametrix, 2003). In general, the groundwater level fluctuates annually and tracks seasonal precipitation levels. Hydrographs developed between February 2001 and November 2003 for HP28-2 and HP28-3 indicate that the wells are dry in the summer months. During some winter months experiencing heavy rainfall, the groundwater levels are observed above ground surface indicating standing water conditions surrounding the well. The actual perched groundwater level fluctuation cannot be determined as a result of the shallow completion depth of the monitoring well that does not intersect the dry season water level. The water level data indicate that the perched groundwater condition seasonally meets wetland criteria (water table within 12 inches of the soil surface) established for the WQC.

3.3.2 Regional Groundwater System

A regional groundwater system has been investigated in the vicinity of the project area during previous hydrogeologic investigations and through the completion of deep water supply wells (AESI, 2000; Kleiber, 1996; and Robinson & Noble, 2000 and 2001). Aquifers have been identified in glacial and non-glacial course-grained deposits in the Qva and Pre-Fraser deposits in the project area near the Port's Lagoon 3 and Tyee Golf

Course areas. These aquifers appear to be confined with some wells exhibiting water level above ground surface (artesian conditions). The confined aquifer conditions and the presence of a low permeability glacial till unit provide a natural barrier to the vertical migration of groundwater contaminants, if present. Therefore, the perched groundwater zone described above appears to be isolated from the deeper Qva aquifer system both hydraulically as a result of upward gradient of the Qva aquifer and by the presence of the low permeability glacial till unit. As a result of natural hydraulic barriers, these deeper water supply wells are not likely to be impacted by the RDF project.

A series of deep water supply wells have been drilled on the Tyee Golf Course by the Highline Water District to evaluate groundwater production potential and replace lost production capacity from an old well (Well 2). In addition, the Port of Seattle operates a deep well used primarily for irrigation of the golf course. These series of wells are referred to the Tyee Well Field for purposes of this report.

Tyee Golf Course Well

The Port of Seattle owns a well (Well 1) that is used for irrigation of the Tyee Golf Course. The well is inside a pump house located near the southeast corner of the golf course north of South 200th Street. The well was completed in November 1949 by Janssen Drilling to a depth of 545 feet bgs. The well is perforated at two intervals between 72 to 160 feet bgs and 190 to 243 feet bgs. The well screen intervals indicate that the well is receiving groundwater from several aquifer units including the Qva and deeper Pre-Fraser coarse-grained units (Figure 3). In addition, the well log indicates that a "sand cup screen" is installed from 511 to 541 feet bgs. The static groundwater level was reported at the time of drilling to be at ground level which indicates confined aquifer conditions. The water level is above the glacial till unit indicating an upward vertical gradient which offers a natural barrier for contaminant migration.

Highline Water District Wells

The Highline Water District has recently completed a well (Tyee well) in the Qva aquifer system at the Tyee Golf Course (Robinson & Noble, 2001). The Tyee well was completed as a replacement for the District's Well 2 which suffered a collapsed screen during rehabilitation work. The well is completed to a depth of approximately 157 feet bgs and is screen between 93 to 150 feet in a sand and gravel unit that is described as the Qva and sediments of the Olympia Interglaciation (Robinson & Nobel, 2001). The groundwater level measured on October 16, 2001 indicated artesian conditions with the water level at 1.1 feet above ground surface. Water quality sampling has been conducted at the Tyee well with arsenic results reported as not detected at levels less than 0.01 milligrams per liter (mg/l) (Robinson & Nobel, 2001).

The Highline Water District also completed a deep well (Well 2M) to a depth of approximately 550 feet at the Tyee Golf Course. Well 2M encountered three aquifer systems consisting of the Qva system and two deeper aquifers in Pre-Fraser sediments (Robinson & Noble, 2000). Well 2M was decommissioned as a result of siting issues associated with the well being completed near Port and Midway Sewer District sewer lines.

3.4 Surface Water

3.4.1 Northwest Ponds

The Northwest Ponds (NWPs) consist of a series of three distinct surface water bodies (cells) that are bounded by wetland vegetation and are located in the headwaters of the West Fork of Des Moines Creek, just southwest of Seattle-Tacoma International Airport (Figure 1). The three ponds are designated Cell NP 1, Cell NP 2 and Cell NP 3, respectively, from west-to-east (Port of Seattle, 2000a). The three ponds are 9 acres in total area and provide approximately 19 acre-feet of dead storage (Port of Seattle, 2000a). The ponds are man-made surface water features resulting from excavation activities associated with peat mining which occurred during the 1960s (Port of Seattle, 2000a). Aerial photographs (Parametrix, 2002 and Walker and Associates, 1998), reviewed for the time period 1936 thru 1997, and historic site plans (Port of Seattle, 1965) show the development of the pond configuration over time.

The ponds vary in depth with the westernmost pond, NP 1, being the deepest at an estimated depth of around 10 to 12 feet, NP 2 estimated between 3 to 5 feet deep and the easternmost pond, NP 3, the shallowest pond with a depth between 2 to 4 feet (Tobiason, 2004).

Drainage to the NWPs has been documented to occur over a total catchment area of approximately 980 acres (Tobiason, 2004). There are four surface water inflows that discharge into the NWPs which include:

- Cell NP 1 receives inflow from two sources consisting of: 1) a small open channel which discharges into the southwest corner of NP 1 (observations suggest this is a stormwater detention system is associated with a private commercial air cargo facility located about 200 feet to the northwest from NP 1 and NP 2), and 2) the NWPs inlet which enters Cell NP 1 from the north and receives drainage from surrounding City of SeaTac commercial areas as well as stormwater discharge from the Port's Storm Drainage System (SDS) outfalls SDS5, SDS6, and SDS7. The NWPs inlet discharge also likely includes the remnant headwaters area of the West Fork of Des Moines Creek.
- Cell NP 2 receives stormwater from the service road adjacent to the Port's Lagoon 3, Port and City of SeaTac commercial areas located west of Lagoon 3, as well as City of SeaTac runoff associated with South 188th Street. This inflow is channelized to an area north of Cell NP 2 and discharges indirectly by broad sheet flow into the wetland area north of Cell NP 2.
- Cell NP 3 receives stormwater from the Port's SDS3 outfall which collects stormwater from over 400 acres and represents the majority of stormwater collected at the airport.

The outflow from the NWPs is continuously gaged near the outlet of Cell NP 3. Gage data collected between 1999 through 2003 indicate an annual average flow of 2.26 cubic feet per second (cfs) with an average low flow observed during September at 0.23 cfs and a high flow average observed during November at 5.41 cfs. Peak daily flows greater than 50 cfs have been measured during several days in the period of record.

As noted above, the ponds contain approximately 19 acre-feet of dead storage that impacts the hydraulic retention time of stormwater entering the system. Water quality studies using ion tracer methods indicated that the stormwater input from SDS3 began exiting the NWPs about 24 hours after entering the pond but was resident in the pond for more than 5 days before it was completely flushed into the West Fork (Port of Seattle, 2000a).

3.4.2 West Fork

The West Fork of Des Moines Creek is a major tributary that flows out of the NWPs complex. The West Fork is about 0.25 miles in length between the outlet of the NWPs to where it joins the East Fork at the confluence located on the Tyee Golf Course. This reach has a very low gradient of approximately 0.1 percent and sparse riparian vegetation. The West Fork experiences depressed dissolved oxygen conditions throughout the year, as well as elevated water temperatures during the summer months (Des Moines Creek Basin Committee, 1997). Stormwater is directly discharged into the West Fork just above the confluence at the Port's SDS4 outfall.

3.4.3 Bow Lake

Bow Lake is a small surface water body located to the southeast of the airport. The lake is the headwaters of the East Fork of Des Moines Creek. Review of aerial photographs and historical documents indicates commercial peat mining activities in the area adjacent to Bow Lake. Peat deposits surrounding Bow Lake have been measured up to approximately 21 feet in thickness. Mining activities have occurred during the 1950s by three operations (Rigg, 1958). The lake and the peat deposit are formed in a depression in the glacial drift sediments (Rigg, 1958). Elevated temperatures and depressed dissolved oxygen conditions have been documented in Bow Lake (Des Moines Creek Basin Committee, 1997).

3.4.4 East Fork

The East Fork of Des Moines Creek originates from the outflow of Bow Lake and flows through a series of subsurface pipes for about 0.5 miles until it daylights around 24th Avenue South. Two stormwater outfalls directly discharge into the East Fork. Each of these outfalls collects stormwater from subbasins (SDE4 and SDS1) within the airport as well as runoff from the City of SeaTac properties located along International Boulevard, South 188th Street and south of the Bow Lake area. The East Fork flows into the Tyee Pond Regional Retention/Detention facility which was a man-made facility constructed in 1989. Tyee Pond provides reduction in peak flows from the 10-year to 100-year interval storm events by detaining live storage for short periods of time after rainfall events. The Tyee Pond provides zero dead storage and has 18.5 acre-feet total storage capacity (Port of Seattle, 2000a). Out flow from the Tyee Pond is transmitted through a 48-inch-diameter pipe where it discharges at the confluence of Des Moines Creek at RM 2.4.

3.5 Land Use and Development

A series of aerial photos, documenting land use conditions between 1936 through 1997, were examined to evaluate land use changes in the project area (Walker and Associates, 1998 and Parametrix, 2002).

In 1936, the area was a mix of farms and second-growth forest. Agricultural use predominated within the basin drained by the West Fork of Des Moines Creek. This area was approximately bounded on the south by South 200th Street, on the west by 8th Avenue South, on the north by South 188th Way (formerly Des Moines Highway) and South 188th Street, and on the east by a north-south line through the intersection of Des Moines Creek with South 200th Street. The current locations of the NWPs and the Tyee Gold Course were plowed fields at that time. The surrounding area exhibits pastures, additional fields including row crops, orchards, and farm sites. The percentage of second-growth forest appears to increase around the edges of the basin as defined above.

A major change in land use occurred with the construction of STIA immediately north of the Des Moines basin. In conjunction with airport construction, the West Fork of Des Moines Creek was ditched and straightened (Port of Seattle, 1942) as evidenced by 1946 photos. The agricultural use remains largely unchanged within the basin. Development of new farm or residential sites can be noted around the basin. Property along the south side of South 196th Place has been developed. There is a small increase in forest cover immediately south of the NWPs location.

Peat was excavated from Bow Lake and the adjacent marsh land during the 1950s (Rigg 1958). A 1960 photo indicates the beginning of peat excavation from what would become the western portion of the Northwest Ponds (Port of Seattle, 1965). By 1967, the western excavation was at its greatest extent, the central excavation pond area excavated in areas to both sides of the Des Moines Creek ditch, and a north-south excavation within the eastern pond outline begun. In 1969, the central pond was a single excavation without the separating ditch and excavations were increased within the eastern pond area. By 1974, the ponds had been excavated to their full extent. The creek outfall was at the current location--the southeast end of the eastern pond.

Most residential and commercial development in the 1950s and 1960s appears to have occurred outside the West Fork basin as defined above. Within the basin, residential development occurred primarily west of the ponds between 8th Ave South and Des Moines Memorial Drive. The largest impacts on the lowland portion of the basin were the peat excavations, golf course development, and industrial and airport expansion. The Tyee Gold Course was constructed by 1974. By 1980, the airport and commercial land use had expanded to include the basin north of the NWPs. Photos taken in 1980 and 1990 document the filling and development of the northern half of the western pond. Since 1946, forest cover has increased modestly around the ponds, principally on the south side.

4 RDF Project Description

4.1 RDF Project Overview and Objectives

The Des Moines Creek RDF Project is a major component of the overall basin plan developed by the Des Moines Creek Basin Committee to restore and improve the creek. It is intended to stabilize the flow regime and reduce channel erosion in Des Moines Creek, especially in the ravine segment of the creek below South 200th Street.

The drainage basin of Des Moines Creek is already heavily urbanized, and under existing land use plans will become even more urbanized. The extensive areas of impermeable surfaces (buildings and pavement) contribute to an unnaturally "flashy" flow regime, with enhanced stormwater runoff resulting in large and rapid increases in stream flows from storm events, and also rapid decreases and reduced base flows (from reduced groundwater recharge). This type of flow regime has degraded stream habitat by increasing flow velocities, increasing channel erosion and downcutting, washing away spawning gravel and large woody debris, and decreasing the number and quality of pools available within the stream. These effects degrade the stream's habitat and reduce the ability of the system to support salmon and resident trout populations, as well as other aquatic resources.

Under existing regulations, future development in the basin will be required to incorporate appropriate stormwater controls. The Basin Committee identified construction of an integrated system of projects, including a regional detention facility as the preferred option to address the cumulative impacts from historical basin development and to reduce peak flows. Figure 8 presents a conceptualized representation of the RDF project features. The two major tributaries of Des Moines Creek, the West Fork and East Fork, are both located in headwaters areas; taken together they represent a little less than half of the creek's total drainage basin area of 5.8 square miles. As a result of this favorable stream pattern, siting a regional detention facility in the headwaters portion of the basin and joining the two tributary areas by a high-flow diversion pipeline offers an effective approach to mitigating the "flashy" flow regime. Anticipated peak discharge reductions (in percent), while diminishing somewhat downstream because of the influence of other small uncontrolled tributaries and base flows, remain significant throughout the downstream region (MGS Engineering Consultants, Inc. 2002). Locating a regional detention facility at the NWPs location was also deemed favorable compared to alternate locations with respect to minimizing land use conflicts and construction costs, avoiding loss of high-quality stream habitat, avoiding increased risks to airplanes from bird collisions, and integrating detention for flows from both headwater tributaries in a single RDF.

The RDF is essentially a large capacity storage area where rapid stream flows from the urbanized upper basin areas will be temporarily detained and released over time, in a controlled manner, back into the stream channel. This will achieve the primary objective of moderating the peak flows in the creek. The final design for the RDF uses two

separate berms, creating a larger primary and a smaller secondary storage area; the secondary storage area will be used only for larger storm events. The basic elements of the RDF project include:

- Modification of the existing NWPs wetland complex involving regarding of approximately 6.4 acres of an existing wetland.
- Realignment of 2160 lineal feet of the West Fork of Des Moines Creek
- Construction of a high-flow bypass pipe to divert high creek flows from the upper basin away from the ravine south of South 200th Street and discharge it directly to Puget Sound.
- Construction of a diversion pipe connecting the East Fork of Des Moines Creek to the NWPs.

Specific elements of the RDF project and the associated construction sequence is presented in the following section.

4.2 Construction Sequence

At least two construction seasons will be required to complete the RDF project. Phase I activities are currently planned to start in early July 2004; Phase II activities will start in about May 2005. Construction activities are detailed in a series of engineering specification drawings (King County, 2003a, 2003b, 2003c and 2003d). In this section, the project description is based on the project "as proposed" prior to any consideration of mitigation measures and project modification to address potential arsenic issues (see Section 8).

Phase I will include the following major activities:

- Excavation of a realigned West Fork channel and abandonment (backfilling or regrading) of the existing channel.
- Planting vegetation along the new channel and placing grade controls.
- Construction of two flow control vaults along the new West Fork channel alignment, at the locations of the West Berm and East Berm.
- Lowering of water levels at the Northwest Ponds to no more than 244.0 feet once the new channel and flow control vaults are completed, before West Berm preload starts.
- Placing the West Berm preload to consolidate subsurface soils, which will include excavation of approximately 3,000 cubic yards of peat (for preload stability) and installation of a lateral dewatering trench.
- Installation of additional dewatering trenches (possible deferral to start of Phase II under discussion).

During Phase I, additional minor activities will be performed: some underground utilities will be removed, a stream crossing for the future Tyee Bypass pipeline will be constructed, and an existing weir in the stream channel will be removed.

Phase II will include the following major activities:

- Lowering of water levels at the NWPs to 242.0 feet.
- Dewatering in planned soil excavation areas (as required).
- Excavation of approximately 45,000 cubic yards of soils to the north and east of the easternmost NWPs, to a final grade of 244 to 245 feet (sloping toward NWPs).
- Construction of the Tyee Diversion pipeline and outfall at NWPs.
- Completion and final grading of the West Berm, including spillway.
- Construction of the East Berm, including spillway.
- Installation of anchor posts and wire grid over open water areas of NWPs.
- Extensive revegetation in soil excavation areas, with shrub/scrub wetlands species.

During Phase II, the major staging/stockpile areas associated with soil excavations will be constructed. A small excavation will also be performed to provide enhanced surface water connection among the NWPs. A bypass will be constructed to reroute surface water inflows to NWPs around the area of planned soil excavation to the north.

Temporary erosion/sedimentation controls will be used throughout the period of RDF construction. All excavated materials will be segregated, dewatered, and either stockpiled for reuse (if clean) or disposed of offsite in an appropriate manner. Major revegetation plantings will occur, probably in the months of November or February.

4.3 RDF Operations

The Des Moines Creek RDF Project will temporarily store storm flows from both the West Fork and East Fork of Des Moines Creek and provide for controlled release of the stored water to the West Fork channel through designed flow control structures. The effect of the RDF project will be to reduce peak discharge rates and flow volumes in Des Moines Creek, thereby reducing erosion in the ravine south of 200th Street, stabilizing the stream channel, and supporting the maintenance of suitable fish habitat. The anticipated hydrologic performance of the RDF project is described in a modeling study (MGS Engineering Consultants, Inc., 2002).

After construction of the RDF project is completed, the average surface water elevations at the NWPs will be lowered by approximately 1.2 feet in winter and 0.5 feet in summer. Flows from frequent annual storms and less frequent, larger storms with relatively small return intervals will be stored behind the West Berm at the Northwest Ponds. During infrequent, larger floods (those exceeding an approximate 10-year return interval) flows will also be stored behind the East Berm in the Approach Light Road Pond. Under existing conditions, areas of the Tyee Golf Course near the NWPs are flooded for extended time periods in most years. With construction of the RDF project, the range of fluctuations in water surface elevations at the NWPs will be greater than under current conditions, but the duration of flooding above pond base elevations will be decreased.

The annual number of flooded-dry cycles on lands adjacent to and somewhat higher than the ponds will therefore be increased during RDF project operation.

The Tyee Bypass pipeline will route some flows from the East Fork of Des Moines Creek around the creek to discharge in Puget Sound. During larger storm events, when the capacity of the bypass line is exceeded, excess flows from the East Fork will be routed to the Tyee Diversion pipeline and discharged to the NWPs through the West Berm. Those discharges during large storms will occur into standing water. A Port stormwater runoff line (SDS 4) that currently discharges to Des Moines Creek will also be connected to the Tyee Diversion pipeline. During smaller storm events, when no East Fork flow is diverted to the NWPs, the SDS 4 discharge into the Tyee Diversion pipeline may occur onto land above the lower water elevations behind the West Berm.

Discharges from the RDF will be controlled by orifices in the flow control structures associated with the West Berm and East Berm. Installation of the final design orifices will be delayed several years after RDF construction is completed to allow time for planted vegetation to grow and be capable of surviving periodic inundation. The orifices may also be modified at a later time as an adaptive management step, if needed to preserve planted vegetation of forested areas or to modify downstream flow levels.

No regular sediment removal actions, or additional soil excavations, are planned for the NWPs detention area as part of normal RDF operations.

5 Environmental Changes Associated with RDF Project

Construction of the RDF project will produce quantities of excavated soils and water (from in situ dewatering actions using excavated trenches, or possibly wells, and dewatering of stockpiled materials) from areas where elevated arsenic concentrations in soils have been documented. A comprehensive construction monitoring program is proposed to monitor arsenic and turbidity levels on a regular basis as part of sediment and erosion control program which is designed to minimize and control construction related impacts to water quality. Stormwater runoff from soil excavation areas could also occur, although significant storm events are infrequent during the planned excavation period and the duration for which excavated areas will be left bare is limited. Handling of these project-related materials will require recognition that arsenic concentrations could be elevated. Appropriate management and/or characterization of these materials will be incorporated as part of RDF construction activities.

The existing environmental conditions will be changed in a number of ways by construction of the RDF. Figure 9 presents a conceptual diagram showing potential arsenic pathways that may occur from environmental changes resulting from RDF construction. Those changes include the following:

- Soil excavations will lower ground elevations within the newly created NWPs detention area to be located north and east of the easternmost NWPs. As a result, soils with elevated arsenic concentrations could be newly exposed at or near the surface.
- Redox conditions and other environmental chemistry and geochemistry conditions of newly exposed soils will be different from pre-RDF conditions experienced by those same soils when they were at depth, before soil excavations.
- The type of soils exposed at or near the surface could change from granular fill to peat, or vice versa, after soil excavations. In some areas, the planned soil excavations could remove the entire thickness of existing peat.
- Soil excavation areas will be graded to provide a consistent, shallow slope toward the NWPs, compared to the current variable, undulating grades and slopes present along golf course fairways. Grade changes may affect surface water flows and infiltration.
- Subsurface disturbances will include emplacement of numerous anchor poles to depths of approximately 30 feet bgs and consolidation of materials beneath the West Berm.
- The West Berm preload will result in a "squeezing" of soil pore spaces and partial dewatering of soils near the berm alignment. Groundwater flows and quality could be affected to some degree.

- The new West Fork channel will be somewhat deeper than the existing channel and will be located south of the existing channel by about 50 to 200 feet. This will affect groundwater flow paths and interception of groundwater to a small degree.
- Dewatering actions in the planned soil excavation areas, as well as changes in topography and the lowering of NWPs water levels, will affect groundwater conditions to some degree. The removal of soils in excavation areas could result in some previously subsurface groundwater flows from uplands areas emerging as springs in the near term as the system equilibrates.
- The range of surface water elevations in storage areas will increase with the RDF project. The duration of flooding per storm event will generally decrease, and the number of flooded-dry cycles per year will increase.
- Changes to inflows to the NWPs after RDF construction could result in some changes to pond surface water chemistry (e.g., DO levels).
- Constructed revegetation of the soil excavation areas will introduce different plant species in current golf course fairway and other areas with potentially deeper root structures and different uptake characteristics.
- The lower elevation for the outlet from NWPs will result in shallower pond water depths for much of the year. This could promote more vegetation growth in the ponds, especially around the margins.
- Peak flows and velocities during storm events will be reduced in the West Fork downstream of the NWPs.

The notable environmental changes associated with the RDF project occur, for the most part, at or near the surface. Conceptually, at some depth below the planned excavations, and in areas below the existing NWPs, pre-project conditions (e.g., groundwater and redox conditions) will remain essentially unchanged after RDF construction.

6 Existing Data

6.1 West Fork Des Moines Creek

Surface water and sediment sample events were conducted on February 13, 2004 and March 30, 2004 by Aspect Consulting to initiate a background monitoring program along the West Fork of Des Moines Creek (Aspect and Glass, 2004). Three surface water and sediment samples were collected to evaluate arsenic concentrations along the reach of the West Fork between the NWPs outlet and the confluence of the West and East Forks during base flow conditions. The purpose of the initial sampling effort was to: 1) confirm and/or refine the conceptual model for environmental cycling of arsenic under current conditions, and 2) extend the overall period of data collection from the existing West Fork channel, which will be abandoned during Phase I construction. The details of the background monitoring program are presented in the Sampling and Analysis Plan (Des Moines Creek Basin Committee, 2004). The following table provides a summary of the background data collected to date.

West Fork Background Data

		Surface Water		Sediment	
Sample Station	Sample Date	Total Arsenic (µg/L)	Dissolved Arsenic (µg/L)	Total Arsenic (mg/kg, dry weight)	% Solids
SW-1a	2/13/04	2.5	2.1	38.3	15.8
SW-1a	3/30/04	1.61	1.33	40.8	9.5
SW-2a	2/13/04	3.1	2.8	47.6	12.7
SW-2a	3/30/04	2.85	2.39	41.5	14.6
SW-3a	2/13/04	3.1	2.7	6.19	54.3
SW-3a	3/30/04	2.72	2.32	13.2	45.3

These data indicate that the arsenic level in the West Fork is well below the surface water quality standards for acute and chronic arsenic criteria of 360 micrograms per liter (µg/L) and 190 µg/L, respectively. Arsenic levels in sediments samples are elevated in concentration at the upstream locations (SW-1a and SW-2a) in comparison to the downstream location (SW-3a).

6.2 Northwest Ponds (NWPs)

The following sections review previous environmental monitoring activities that have been documented at the NWPs.

6.2.1 Sediment Sampling

In October 1995, Resource Planning Associates (RPA) analyzed sediment from the Northwest Ponds. Samples were taken from all three ponds (six from the east pond, three in the central pond, and three from the west pond). The sediments were tested for the following analytes: pH, total petroleum hydrocarbons (TPH), total solids (TS), total preserved solids (TPS), total volatile solids (TVS), total Kjeldahl nitrogen (TKN), phosphate-ortho (TP), sulfide, and metals (aluminum, copper, lead, and zinc). Arsenic was not included in the laboratory testing.

The primary finding was elevated levels of petroleum products. Samples from the west pond tested from 7,200 to 12,000 parts per million (ppm) TPH. The TPH levels were at lower levels in the central and eastern ponds, 550 to 4,300 ppm and 760 to 1,500 ppm, respectively. One sample from the west pond exhibited a lead concentration of 1,010 ppm. Aluminum levels ranged between 5,780 to 40,300 ppm.

Subsequent work was undertaken in 1996 (EcoChem, Inc., 1996), with a particular emphasis on identifying the types of petroleum products documented during the previous fall season. Additional sediment samples were collected during May, 1996 near the same locations as the 1995 sample event. The IWS Lagoon 1 and the South 188th Catch Basin were sampled in June, 1996 as an aid in the identification of potential sources.

The sediment samples were initially analyzed for petroleum hydrocarbons in the ranges for diesel (C12-C24) and motor oil (C24-C40). However, the chromatograph distributions better matched weathered Jet A fuel. Therefore, the data were requantified for Jet A (C9-C18) and motor oil (C18-C34).

At the west pond, the three samples had TPH concentrations ranging from 8,800 to 13,800 ppm (C9-C34). Concentration was highest near the inlet and decreased with downstream distance. Based on the quantification against the Jet A standard, the petroleum hydrocarbons are approximately 82 to 87 percent motor oil and 13 to 18 percent Jet A. The portion classified as Jet A was believed to also include some weathered diesel. The presence of diesel was indicated by: (1) the number of individual alkyl peaks, and (2) an extension of the lower molecular weight end of the motor oil portion of the chromatograph curve as compared to that observed in the South 188th Catch Basin. The TPH signature of Lagoon 1, whose stormwater overflow could enter the west pond, indicated 80 percent Jet A. Therefore, the sources of petroleum hydrocarbons into the west pond were estimated to be 25 percent from Lagoon 1 and the balance from roadway runoff.

Three samples were taken near the outlet of the east pond. TPH concentrations were in the range 1,590 to 3,960 ppm (C9-C34). The petroleum types were judged to be approximately 80 percent motor oil, 20 percent a mid-range constituent, such as weathered diesel, and possibly a low concentration (50 ppm) of only moderately weathered gasoline. The chromatographs showed no clear indication of weathered Jet A.

6.2.2 Des Moines Creek Basin Plan

The Des Moines Creek Basin Committee prepared a Basin Plan in 1997, which highlighted two primary problems in the Des Moines Creek Basin caused by alterations of runoff patterns in the urban environment. These problems are: 1) an increase in peak

flows, with resulting flooding and erosion problems, and 2) a reduction in baseflows that aggravates water quality problems and negatively impacts fish habitat. In order to reduce the impacts of peak flows, the Committee proposed:

- Increasing the retention/detention capacity of the NWPs,
- Limiting the peak flow from the Ponds,
- Providing a diversion pipe to direct overflow from Tyee Pond into the NWPs, and
- Providing a bypass pipe to route part of Des Moines Creek flows directly to Puget Sound.

These proposals have since been formalized in the Des Moines Creek Regional CIP plans (King County, 2004a, 2004b, 2004c, and 2004d).

The City of Des Moines and the Port of Seattle had ongoing water quality monitoring programs at the time of the Committee's report. The NWPs do not appear to have been specifically included in the City's scope of work. The Port necessarily included the NWPs as part of the system for stormwater discharge from the airport into Des Moines Creek. One specific item in the report was to determine the ecological state and functions of wetlands surrounding the airport, including the NWPs. The Committee's report expressed concern about the low dissolved oxygen concentrations in the creek north of South 200th Street. Low dissolved oxygen (DO) and high temperatures were specifically noted in the NWPs and the West Fork of Des Moines Creek (Des Moines Creek Bain Committee 1997, p. B-17 and B-25). Potential effects of deicing fluids were also of concern (see Section 6.2.3). Arsenic was not listed as a tested parameter (Des Moines Creek Basin Committee 1997, Table 3.3).

6.2.3 Port of Seattle Studies on Effects of Deicing Fluids

The Washington State Department of Ecology (DOE) expressed concern that the biochemical oxygen demand (BOD) of deicing fluids could affect DO levels in streams adjacent to the airport. One drainage path is into the Northwest Ponds and thence into Des Moines Creek. The Port conducted two studies to address dissolved oxygen effects (Cosmopolitan Engineering Group, 1999 and Port of Seattle, 2000a).

The 1998-1999 study concluded that deicing chemicals passed quickly through Des Moines Creek. DO levels were lowest in the NWPs, but oxygen concentration rose rapidly downstream along Des Moines Creek. There was no reduction in DO concentration when deicing chemicals were detectable in runoff. DO levels increased during periods of rainfall and decreased during dry periods.

Because of the rapid aeration of water in the creeks, the 1999-2000 study focused only on the ponds. DO, conductivity, temperature, and other parameters were monitored continuously in the centers of the western and central ponds and near the outlet of the easternmost NWPs. The study again found that DO levels fluctuated with rainfall. DO values typically dropped to 25 percent saturation during dry weather and as low as 5 percent during one extended dry period. The study was not able to identify effects on DO due to deicing chemicals.

Sampling of vertical profiles of the water columns revealed persistent stratification of dissolved oxygen in the NWPs. The stratification was most predominant in the western and central ponds. In those ponds, a persistent oxycline, 2 to 3 feet thick, was found that separated an upper oxygenated layer (5-11 mg/L) from a lower low oxygen layer (<1 mg/L). (An oxycline was seldom present in the east pond.) Vertical position of the oxycline varied over time from 3 to 8 feet below the surface. Runoff increased DO concentrations in the upper layer, but in the lower column the concentrations tended to remain low. The abrupt increase of DO levels with runoff was followed by a steady decline during dry weather. The patterns in conductivity measurements mirrored those for DO. That is, conductivity dropped quickly during rain events and rose steadily during periods of dry weather. Temperature gradients were noted in the ponds and may resist vertical mixing. The stratification in the ponds was thought to be caused by a natural oxygen demand of accumulated organic material on the pond bottom and/or the underlying layer of peat.

6.3 King County Soil Chemistry Investigations

King County Department of Natural Resources and Parks (KCDNRP) has completed two phases of a soil investigation program designed to provide upland and wetland soil chemistry data for a number of sample locations within the Cell 1 and Cell 2 excavation areas. The purpose of the County's soil sample program was to provide data to evaluate disposal and end-use options for approximately 45,000 cubic yards (cu. yd.) of excavation spoils resulting from lowering the existing ground surface to approximately elevation 245 feet. The results of the sampling program were intended to provide soil chemistry data for evaluation of excavated soil handling options, identification of staging areas, soil disposal/treatment options, and other end-use options for clean soil such as in-fill for the abandoned section of the Des Moines Creek channel and slope dressing. A summary of the two soil investigation programs is presented in the Sampling and Analysis Plan (Des Moines Creek Basin Committee, 2004) and is briefly discussed below. Figure 10 provides a summary of the arsenic levels measured in soil samples collected by King County.

The Phase I soil investigation was conducted between August 19, 2003 through August 21, 2003 consisting of 15 sample locations in Cell 1 and Cell 2 excavation areas and three locations along the new Des Moines Creek channel alignment. A total of 18 composite samples were submitted for laboratory analysis. The data indicated that arsenic was the only compound of concern. Arsenic was detected at five of 18 sampling locations at concentrations above the Model Toxics Control Act (MTCA) Method A cleanup level of 20 mg/kg. Detected arsenic concentrations in the composite samples ranged between 3.2 mg/kg and 78.3 mg/kg. As a result of the composite sampling procedure, the vertical distribution of arsenic at the sample location could not be determined.

A Phase II soil sample program was conducted to further refine and evaluate the vertical and horizontal extent of arsenic impacted soil. The Phase II investigation was based on recommendations of a Value Engineering study that recommended collection of discrete depth samples to evaluate the vertical distribution of metals in soil. The Phase II soil investigation was completed between October 23, 2004 and October 24, 2003, which provided discrete interval soil samples from supplemental soil borings. A total of 42

2003?

samples were analyzed for arsenic and chromium and 12 samples for mercury to evaluate the vertical distribution from the twenty additional locations. Arsenic ranged in concentration from non-detect to 432 mg/kg. Arsenic was detected at levels greater than the MTCA Method A cleanup level (20 mg/kg) in 17 samples. Nine out of the 11 sample locations exhibited an arsenic concentration gradient increasing with depth. These locations had elevated levels of arsenic near the bottom of the boring at depths approximately 5 feet bgs. Mercury was detected in one sample (NWPRDF-15W) near the surface at 2.71 mg/kg, which is above the MTCA Method A cleanup level of 2 mg/kg.

The Phase II data indicate that elevated arsenic would be present near the proposed RDF excavation depth, raising concern for the potential of arsenic transport and impact into surface water.

6.4 Port of Seattle Stormwater Monitoring Programs

The Port has historically analyzed for arsenic as part of their National Pollutant Discharge Elimination System (NPDES) and other stormwater monitoring programs from outfalls discharging into the East and West Forks of Des Moines Creek. Arsenic has been monitored at two outfalls (SDE4 and SDS1) discharging to the East Fork, and one outfall (SDS4) discharging to the West Fork, and one outfall discharging to the West Fork through the NWPs (SDS3) between 1994 through 1998. As a result of consistent low arsenic levels detected during this monitoring program, Ecology dropped arsenic as a NPDES stormwater monitoring parameter (Tobiason, 2004). A Site-Specific Water Quality Assessment (SSA) Study (Brix, Stubblefield, Deforest, 2002) included a single arsenic sampling event at the three outfalls (SDE4, SDS3, and SDS4) described above.

Surface water samples of priority pollutant metals from the 1994-1998 NPDES Storm Characterization Sampling (Tobiason, 1996, 1997, and 1998) and from the SSA Study include arsenic results at four of the outfalls discharging into Des Moines Creek. Results from these analyses show arsenic concentrations at significantly lower levels than the State surface water quality standards. A summary of these results appears in the following table.

Summary of Historic Arsenic (Total Recoverable) Samples (1994-2001) Collected At Outfalls Discharging Into Des Moines Creek							
			East Fork Outfalls				
Outfall	**#Samples**	**#Detects**	**#Non-Detect**	**%Non-Detect**	**Detect Max (µg/l)**	**WQS Acute (µg/l)**	**WQS Chronic (µg/l)**
SDE4	21	11	11	50%	7.2	360	190
SDS1	18	9	9	50%	5.1	360	190
			West Fork Outfalls				
Outfall	**#Samples**	**#Detects**	**#Non-Detect**	**%Non-Detect**	**Detect Max (µg/l)**	**WQS Acute (µg/l)**	**WQS Chronic (µg/l)**
SDS3	22	11	12	52%	4.0	360	190
SDS4	21	8	13	62%	4.3	360	190

As described in Section 9.1, the Port is currently implementing additional stormwater monitoring at sample locations along the West Fork of Des Moines Creek and will be monitoring several stormwater events for a range of analytes including arsenic.

7 Conceptual Model for Arsenic Mobility

Arsenic is a naturally occurring element that is ubiquitous in the atmosphere, soils and rocks, natural waters and organisms. It can be mobilized and/or immobilized in the environment through a combination of natural processes such as weathering reactions and biological activity, as well as through a range of anthropogenic activities. Arsenic mobility in soils and water is controlled by its speciation, which depends on pH, redox conditions and availability of other elements (iron, sulfur, etc.). Many of the concerns raised about arsenic in the environment are the result of arsenic mobilization under natural conditions, although industrial (mining and mineral processing, combustion of fossil fuels) and agricultural (use of arsenical pesticides, herbicides and crop desiccants and the use of arsenical additives to livestock feed) activities can be important as well (see following references at the end of Appendix B: Welch, et al., 2000; Smedley and Kinniburgh, 2002; Smedley et al., 2003; Welch and Stollenwork, 2003).

Predicting the potential for arsenic mobilization in RDF site soils in response to environmental changes resulting from the construction of the RDF requires an understanding of the factors and processes controlling the behavior of arsenic in the environment.

7.1 Arsenic Forms and Factors Affecting Mobility

The relevant aspects of the environmental geochemistry of arsenic as they relate to the RDF site are summarized below and on Figure 11. A more detailed account is provided in Appendix B.

- Arsenic mobility is controlled by its speciation or chemical form, which depends on pH, redox conditions, and availability of other elements such as iron and sulfur.
- Arsenate or As(V) species are stable under oxidizing conditions.
- Arsenite or As(III) species are stable under reducing conditions.
- In natural waters, As(V) species are present as anions (negatively charged ions); their mobility is limited by interactions (adsorption and coprecipitation) with soil particle surfaces (iron, aluminum, manganese oxides, clays, organic matter).
- As(III) is present as a neutral molecule; its mobility is also limited by interactions with soil surfaces, but it is generally more mobile than As(V).
- Adsorption is pH-dependent, with maximum uptake at near-neutral pH conditions (6-8), but can be reduced by competing ions such as phosphate and silicate, if these are present at sufficient concentrations.
- Under suitable conditions, As(III) can be transformed to As(V) and vice versa. As(III) can be oxidized to As(V) by oxidants such as dissolved oxygen, nitrate, and ferric iron). As(V) can be reduced to As(III) by reducing agents, such as

organic matter and sulfide. Although these transformation reactions may be very slow under ambient conditions, they can be catalyzed by microbial activity.

- In relatively oxidizing soil environments where As(V) is immobilized by adsorption and/or coprecipitation with iron and/or manganese oxides, flooding for extended periods of time can lead to reductive dissolution of the oxides thereby releasing As(V).
- In environments where sulfate reduction to sulfide is occurring, As(III) combines with sulfide (and iron) to form insoluble precipitates (realgar, orpiment, arsenic-bearing iron sulfides).
- If oxidizing conditions are introduced where arsenic-containing sulfide precipitates previously formed, the sulfides can be oxidized thereby releasing the arsenic.

7.2 Biogeochemical Cycling of Arsenic

A preliminary conceptual model for arsenic cycling within the RDF project area is presented below and on Figure 11. Model development was accomplished by integration of available site data and comparison to published models for arsenic biogeochemical cycling in similar environments. A brief summary and bibliography of the publications reviewed are presented in Appendix B.

- Arsenic may enter the NWPs through surface water and/or groundwater inflows. The magnitudes and relative importance of these fluxes are not known at present.
- High algal productivity observed within the NW ponds results in seasonally anoxic conditions. This is expected to give rise to seasonal redox cycling of arsenic in the pond water column as well. During winter, oxygen-rich conditions prevail and part of the arsenic entering the ponds will be removed by adsorption onto settling particles which accumulate as bottom sediment. From spring to fall, anoxic conditions appear to develop in the water column and may result in partial release of arsenic in bottom sediments back to the water column.

Under existing conditions, transport and attenuation distances of dissolved As along the West Fork of Des Moines Creek are expected to depend on its speciation in the NWPs and may vary seasonally. As(III) is likely to be transported further downstream than As(V) because of weaker sorption. During the summer, organic forms of arsenic (e.g., methylated species produced by algae) may also be important in the pond water.

7.3 Potential Project-Related Arsenic Releases

This section discusses potential arsenic releases that could result from the RDF construction. Planned activities for which a potential for release of arsenic-bearing water exists include excavation and berm pre-loading. Potential for both short-term and long-term impacts to the West Fork of Des Moines Creek are considered.

The basin restoration projects are not expected to significantly impact the existing arsenic cycling within the ponds as described in the previous section.

Due to the reducing conditions in peat, arsenic is most likely present as As(III). As(III) is likely to be present dissolved in pore water, as well as adsorbed on organic matter. In deeper peat horizons with higher arsenic concentrations and where hydrogen sulfide has been noted, arsenic sulfide precipitates are also likely to be present. Some As(V) may also be expected in proximity of ground surface due to exposure to atmospheric oxygen. As(V) in near-surface peat is most likely adsorbed to humus and mineral surfaces (iron, manganese oxides, clays).

During excavation of peat, subsurface horizons that are currently anoxic would be brought to the surface. This could result in a short-term release of arsenic-bearing pore water as well as a slow release of arsenic adsorbed on peat and associated with sulfides by leaching and oxidation. The slow release of arsenic from the excavated peat surfaces will be a temporary phenomenon. After the newly excavated surfaces become exposed to natural weathering processes, conditions in the peat are expected to approach pre-excavation conditions at some point in time after the excavation is completed.

During the berm preload period, some quantity of porewater beneath the berm is likely to be displaced and may discharge arsenic-bearing water to the surface. This would constitute a potential short-term release.

Although the duration and magnitude of these anticipated temporary releases cannot be predicted with confidence at present, these are the focus of ongoing investigations. A sampling and analysis program designed to provide the data needed to answer these questions has been submitted (Des Moines Creek Basin Committee, 2004).

Potentially applicable mitigation/control measures for dealing with the potential arsenic releases described above are reviewed in the following section.

8 Potential Project Design Modifications

A number of potential project design modifications have been identified that would provide protective measures to Des Moines Creek from RDF construction activities, if deemed necessary. The modifications would be designed to ensure that the project would not result in increased arsenic mobility from peat horizons exposed by excavation and affected by project operations. The following sections provide a brief description of the proposed modifications.

8.1 Over-Excavation and Installation of Clean Cap

An evaluation of the horizontal and vertical extent of arsenic will be further refined after additional soil sampling is completed and data evaluated during the baseline sampling program (see Section 9.2). Based on the existing soil data collected by King County, elevated levels of arsenic are present in peat soils in the northern portion of Cell 1 and the eastern area of Cell 2 (Figure 10). In the next phase of soil sampling, samples will be collected at 53 locations along a grid established in Cell 1 and Cell 2. Depth specific soil samples will be collected and analyzed for arsenic. The samples will be collected at approximate one foot intervals to a depth of 2 feet below the proposed RDF excavation grade.

Based on the results of the previous and supplemental soil sample events, an analysis will be performed to determine the area and depth of possible over-excavation to remove arsenic impacted soil during Cell 1 and Cell 2 construction. It is anticipated that the depth of the over-excavation will be limited by shallow groundwater conditions and dewatering constraints at the time of construction. In addition, the complete removal of organic rich peat soils in some areas could reduce the adsorptive capacity of the site (i.e., reduce the natural protectiveness of the site with respect to any continuing arsenic mobility).

The over-excavation will be completed such that an appropriate thickness of iron amendment (see Section 8.2) and a clean soil cap can be placed at the required elevation grade of between 244 to 245 feet. The clean cap will be comprised of material excavated on site (i.e., new West Fork channel alignment) which meet end-use requirements. The clean cap will provide an erosional buffer surface to isolate the arsenic laden soil and protect the iron amendment material, as well as limit contact to soil containing elevated arsenic, which is not excavated during construction. The clean cap will also provide a horizon for the establishment of the scrub-shrub vegetation cover.

The RDF project is currently located within a limited access area of the Tyee Golf Course which is Port owned property. The Port currently limits access to the site through locked and gated fencing which is monitored by Port security patrols. Additional fencing could be established around the over-excavated and capped areas as necessary to limit direct contact exposure, if necessary.

8.2 Soil Amendments

Slow releases of arsenic from leaching of freshly exposed soil/peat at the ground surface in the Cell 1 and Cell 2 excavation area may be mitigated naturally by adsorption and coprecipitation with iron hydroxides (produced by oxidation of iron sulfides in peat). The effectiveness of this natural attenuation mechanism will depend on the concentration of iron available to form iron oxides, and its rate of formation relative to the leaching rate of arsenic.

If the abundance of iron is too low, or its oxidation rate too slow under ambient conditions, formation of iron oxides in the peat surface layer (top 6 inches to 1 foot) could be enhanced by amendment of exposed peat surfaces with iron in a more readily oxidizable form. Potentially suitable amendments include zero-valent iron (granular or steel wool) and/or various soluble iron salts (ferrous sulfate, ferric sulfate, etc.).

The need for, chemical form of, and dosage of iron amendment will be evaluated through detailed characterization and testing of soil/peat samples collected from planned excavation depths. This will include aerobic leach testing on multiple unamended and amended splits. Details of the planned testing are summarized in the Sampling and Analysis Plan (Des Moines Creek Basin Committee, 2004).

8.3 Water Collection and Treatment

Excavation in Cell 1 and Cell 2 may require dewatering of the project area to facilitate construction. The dewatering requirements are currently being developed by the construction design manager for implementation prior to the Phase II construction season (Spring-Summer 2005). Dewatering may be accomplished using shallow ditches that are constructed in the Cell 1 and Cell 2 excavation area. The water removed by the dewatering process will be monitored during the Construction Monitoring Program (Des Moines Basin Committee, 2004 and Hansen and O'Rollins, 2003)for turbidity and arsenic levels. Appropriate Best Management Practices (BMPs) will be implemented as necessary based on monitoring results. The BMPs proposed to treat turbid water include temporary settling basins and/or bio-filtration to remove sediment or, if necessary, containment and settlement in portable settling facilities (baker tanks) followed by treatment using chemical flocculation (Hansen and O'Rollins, 2003). Results from the groundwater monitoring proposed during the Baseline Monitoring Program will be used to refine the treatment alternatives, as necessary, for the removal of arsenic (see Section 9.2 and Des Moines Basin Committee, 2004).

In addition, material excavated during the RDF project will be temporarily stockpiled in staging areas. Water draining from these materials will be controlled by BMPs (see Section 1.2.2 of Hansen and O'Rollins, 2003) to ensure that Des Moines Creek is not impacted. Turbidity and arsenic levels of water exiting the sediment traps or settling pond will be monitored on a daily basis throughout the construction period.

8.4 Adaptive Management

Adaptive management measures will be implemented, as necessary, during the construction and/or post-construction period contingent on monitoring results or as

conditions warrant. Data collected during that construction and post-construction period will be evaluated to determine if BMPs and/or project design modifications are functioning properly. If the data indicate additional measures are deemed necessary, adaptive management alternatives will be evaluated to screen the most appropriate technology to implement. Several potential alternatives include:

- Potential short-term arsenic releases during the excavation and preload period can be prevented by collection of discharged water and containment in Baker tanks as described above. Collected water can be treated on-site with commercially available water treatment chemicals such as ferric chloride coagulation and settling or other similar methods. The treated water, once tested and shown to meet discharge criteria for arsenic and suspended solids, could then be discharged to either the pond or creek. Treatment residuals in the Baker tanks would be cleaned out periodically, tested, if necessary, and disposed appropriately.
- If additional polishing treatment is required to meet discharge criteria, the outlet flow control structure could potentially be modified to allow a mobile adsorption treatment unit (or other appropriate filter technology) to be installed inline to the discharge line.
- Additional source evaluation could be conducted to evaluate arsenic input into the wetland environment. Based on the results of the evaluation additional removal, reduction or control could be established to decrease levels of arsenic accumulation.
- If monitoring data indicate elevated levels of arsenic in groundwater discharging directly to surface water, a groundwater collection and treatment or hydraulic barrier system could be established.

9 Proposed Monitoring Programs and Objectives

A comprehensive monitoring program is proposed to evaluate environmental conditions prior to, during and after construction of the RDF. Specific details on the monitoring objectives, field sampling programs, laboratory testing and analysis, data evaluation and schedule are presented in the previously submitted Sampling and Analysis Plan (Des Moines Creek Basin Committee, 2004). The following sections provide an overview and the objectives of the proposed monitoring programs.

9.1 Pre-Construction Monitoring Program

With respect to the RDF project, the evaluations of potential arsenic mobility have focused on project-related impacts. A pre-construction monitoring program for collection of data on arsenic levels in the West Fork, directly downstream of the NWPs outlet, is therefore proposed to identify the degree to which the presence of elevated arsenic levels at the NWPs area has already impacted the creek, before RDF construction begins.

The pre-construction monitoring program includes collection and analysis of sediment and surface water samples from three locations in the West Fork, between the NWPs outlet and the confluence of the West Fork and East Fork of Des Moines Creek. Sediments likely reflect an accumulative sink for cumulative historic releases of arsenic, if any, from the NWPs. An initial sampling event was conducted in February, 2004, as the Sampling and Analysis Plan was being prepared. Additional sampling events are to be scheduled approximately monthly between March and July, before the start of Phase I of RDF construction. With Phase I construction scheduled to start by July, 2004, and with abandonment of the existing West Fork channel to be accomplished as part of Phase I field activities in summer 2004, it will not be possible to collect surface water samples from the existing West Fork channel to represent a full cycle of annual seasonal variation. However, sediment data should represent cumulative impacts of any pre-construction arsenic releases.

Independent of the proposed RDF pre-construction monitoring program, the Port of Seattle will also be collecting surface water samples in the West Fork near the outlet of the NWPs, among other locations. The Port's sampling program (for development of site-specific water quality standards for copper and zinc) will include arsenic as an analyte and will focus on sampling during stormwater discharge periods. At least 8 sampling events are planned between March and December, 2004; the initial sampling rounds will also provide arsenic data characterizing pre-construction conditions in the West Fork during stormwater events.

9.2 Baseline Monitoring Program

The evaluations of potential arsenic issues arising from the discovery of elevated arsenic concentrations in the vicinity of the NWPs produced a conceptual model for arsenic

environmental cycling and the likely factors affecting arsenic mobility at the RDF location. A baseline monitoring program, involving sampling of multiple environmental media, extensive analytical testing, and collection of samples over four quarters to evaluate seasonal variations, is proposed to confirm and refine that conceptual model. The results of baseline sampling will also be used to support a number of decisions on project design and the incorporation of mitigation measures to address potential arsenic releases due to the RDF project.

The baseline monitoring program schedule will include one sampling event before the start of Phase I construction, and three quarterly sample events during Phase I or between Phase I and Phase II. The collected data will therefore reflect both pre-construction and construction periods. However, the primary objective for the baseline monitoring program is not to provide pre-construction data or to perform construction monitoring (although the data will reflect those periods). It is instead focused on evaluating arsenic environment cycling and supporting further project design decisions. To meet these objectives, the baseline monitoring program includes much more extensive sampling and analytical approaches than the more focused pre-construction and construction monitoring programs.

Preliminary soil sampling by King County in planned soil excavation areas provides some information on the distribution of arsenic. A more extensive and detailed grid sampling of soils (with more than 300 samples analyzed) will be included in the baseline monitoring program. The resulting data set will support decisions on soil excavation areas and depths for Phase II construction, segregation and management of excavated materials, and volume calculations on available materials for use as a clean cap. All collected samples will initially be analyzed for arsenic, based on those results, additional cores will be collected at selected grid locations for more detailed analyses related to arsenic mobility and treatment. All soil sampling will occur in the first quarter of the baseline monitoring program. The second phase of soil analyses will provide data to support decisions on whether in situ soil treatment is needed, and if so what treatment design should be used.

The baseline monitoring program will also include coordinated sampling of surface water, sediment, and groundwater. Paired surface water and sediment samples will be collected at four locations in the NWPs and three locations in the West Fork of Des Moines Creek, between the NWPs outlet and the confluence with the East Fork. (Sampling in the West Fork will start in the existing channel and then move to the newly realigned channel constructed in Phase I.) Groundwater samples will be collected at seven locations, four within the planned soil excavation areas near the NWPs and three near the surface water sampling locations in the West Fork. Two separate depth intervals will be sampled in a well cluster at each of these 7 locations. The coordinated program for sampling surface water, sediments, and groundwater will be performed quarterly. Analytical results from these samples will be evaluated, in conjunction with the soil sampling results, to better understand arsenic environmental mobility and controlling factors at the RDF project location. The groundwater data will also provide information on the arsenic levels in shallow groundwater and required handling of dewatering water (to be collected in Phase I and/or Phase II construction periods) in soil excavation areas.

The extensive baseline monitoring program data set will be also be reviewed to determine whether any changes to subsequent monitoring programs should be made.

9.3 Construction Monitoring Program

Construction of the RDF will require the collection and proper management of water from dewatering trenches (or wells), water draining from stockpiled materials (i.e., excavated soils), and possibly from stormwater runoff (e.g., at soil excavation areas). It will be important to verify that any such waters being discharged to surface waters are of suitable quality for direct discharge, or that appropriate management protocols (collection and treatment prior to discharge, or other disposal arrangements) are used if needed. Therefore, during both the Phase I and Phase II construction periods there will be frequent sampling and arsenic analysis of water collected in dewatering operations, drainage from stockpile areas, stormwater runoff, or any other volumes of water potentially discharging from work areas. These additional arsenic analyses will supplement previously planned turbidity monitoring.

In addition, surface water samples will be collected and analyzed for arsenic on a frequent basis from the West Fork of Des Moines Creek near the outlet from the NWPs. (In the early part of the Phase I construction period, the sampling location will be in the existing West Fork channel; after rerouting of flows to the realigned channel in Phase I, and throughout Phase II, samples will be collected from the newly constructed channel.) That West Fork sampling location will check for any impacts at the surface water discharge point from all areas disturbed during RDF construction.

The general approach to arsenic analyses for surface water samples in the construction monitoring program will be to use arsenic field test kits extensively for screening evaluations that provide real-time results supporting field management decisions. In the initial stages of construction monitoring additional samples will be sent to an analytical laboratory for analysis, to verify the performance of the field test kits. Samples with elevated field results will also be sent to an analytical lab for confirmation and better quantification of arsenic levels.

Placement of the West Berm preload during Phase I of the RDF construction will result in consolidation of underlying soils, resulting in displacement ("porewater squeeze") of some groundwater. In areas near the south end of the West Berm preload, the pathway from the consolidating soils to either the easternmost NWPs or the West Fork of Des Moines Creek is relatively short. Data will be collected from a series of approximately eight temporary groundwater wells installed in this area before the start of Phase I construction to characterize the likely arsenic concentrations in displaced groundwater. (Information from the extensive grid sampling of soils [see Baseline Monitoring Program] will also provide information on soil arsenic concentrations in this area prior to starting the preload activities.) These data will be evaluated to determine if collection and management of groundwater during the West Berm preload period is advisable.

Much of the extensive baseline monitoring program will occur during the Phase I construction period (see Section 9.2); the post-construction monitoring program will also be extended earlier in time to cover the Phase II construction period (see Section 9.4). Those monitoring programs will therefore also provide data during RDF construction,

including sampling of additional environmental media (e.g., sediments and groundwater), that will supplement the frequent surface water sampling described above for the construction monitoring program. The Port of Seattle's stormwater monitoring program (see Section 9.1) will also include several storm events during the Phase I construction period, providing additional data.

9.4 Post-Construction Monitoring Program

Once RDF construction is completed, there will be two major potential pathways for arsenic releases from the RDF project area: via surface water discharges from the NWPs to the newly realigned channel of the West Fork, and via shallow groundwater flows that will discharge to the West Fork. A post-construction monitoring program is proposed to evaluate arsenic conditions along these potential release pathways.

Post-construction sampling will include collection and analysis of surface water and sediment samples at three locations in the West Fork, between the NWPs outlet and the confluence with the East Fork, and at one shallow screened interval in each of three groundwater wells installed near to, and upgradient from, the West Fork sampling locations. Creek sediments are likely to constitute an accumulative sink for any ongoing releases. The array of three sampling locations will provide information along a spatial gradient downstream of the RDF project.

Post-construction monitoring is proposed to be conducted for a period of 8 years, beginning at the end of the Phase II construction field program. That period should reasonably reflect a range of annually variable conditions as well as the re-establishment of long-term (equilibrium) post-disturbance conditions after RDF construction. An extended period of monitoring will support time trend evaluations of arsenic concentrations downstream of the RDF project. The initial sampling frequency will be quarterly; data will thus be collected to reflect seasonal variations. After 3 years, and based on evaluation of the cumulative post-construction monitoring data set, a reduction in sampling frequency to semiannually may be proposed to Ecology. Post-construction monitoring may be terminated after 8 years unless project-related impacts have been documented.

RDF construction will extend over at least 2 construction years (Phases I and II). The extensive baseline monitoring program will end before the start of Phase II field activities. To avoid having a period between the baseline and post-construction monitoring programs when comparable downstream data in the West Fork will not be collected, the post-construction sampling and analysis program will also be performed quarterly throughout the Phase II construction period. This will provide a continuous data set from the start of baseline monitoring, supporting long-term time trend evaluations. The inclusion of sediment and shallow groundwater sampling in this sampling approach will complement the focused surface water sampling during the construction monitoring program.

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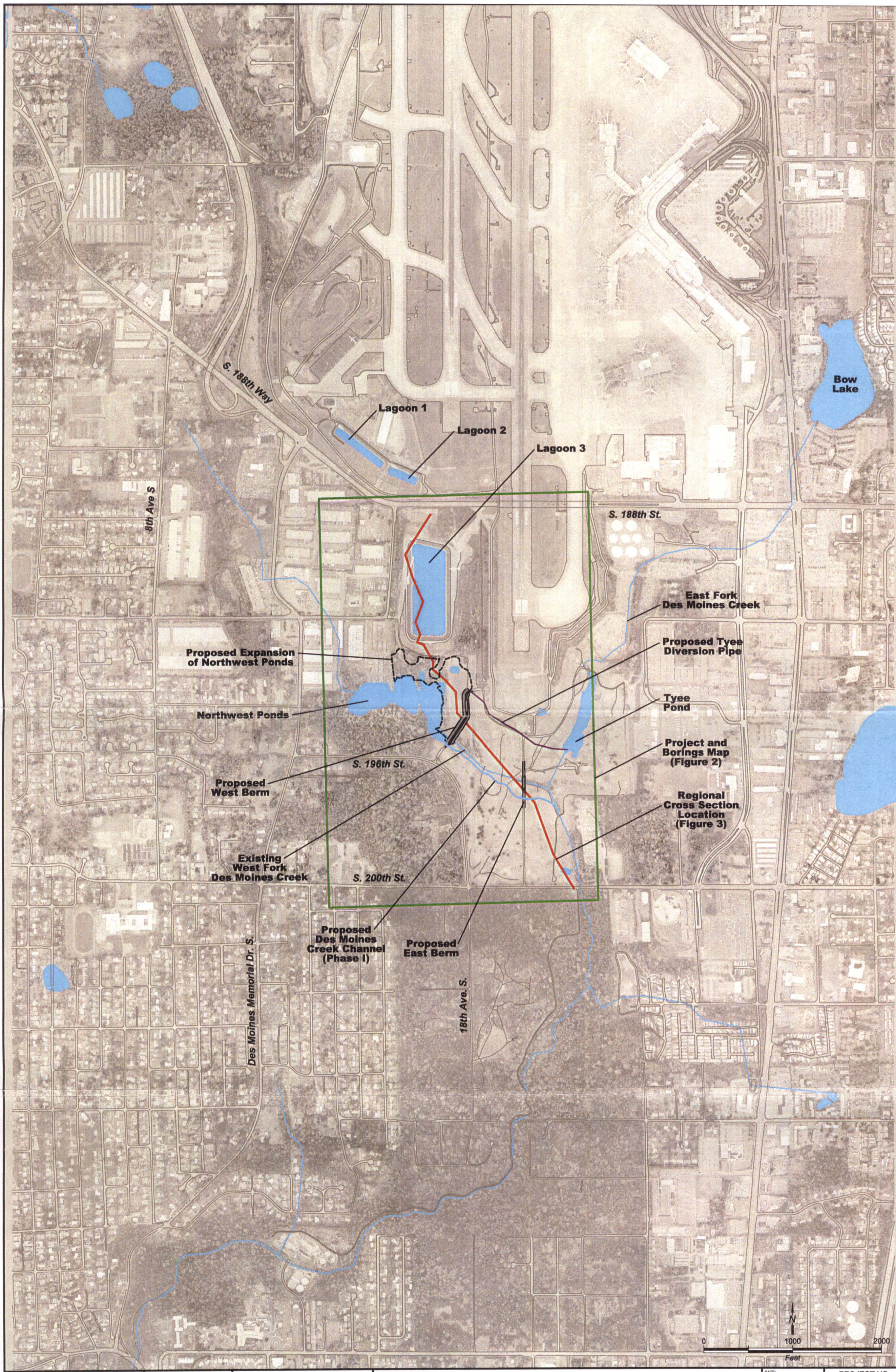
Limitations

Work for this project was performed and this report prepared in accordance with generally accepted professional practices for the nature and conditions of work completed in the same or similar localities, at the time the work was performed. It is intended for the exclusive use of Des Moines Creek Basin Committee for specific application to the referenced property. This report does not represent a legal opinion. No other warranty, expressed or implied, is made.



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Site Location Map

Des Moines Regional Retention/Detention Facility
SeaTac, Washington

DATE:	April 2004
DESIGNED BY:	JSL
DRAWN BY:	SDM
REVISED BY:	PMB

PROJECT NO.
030185

FIGURE NO.
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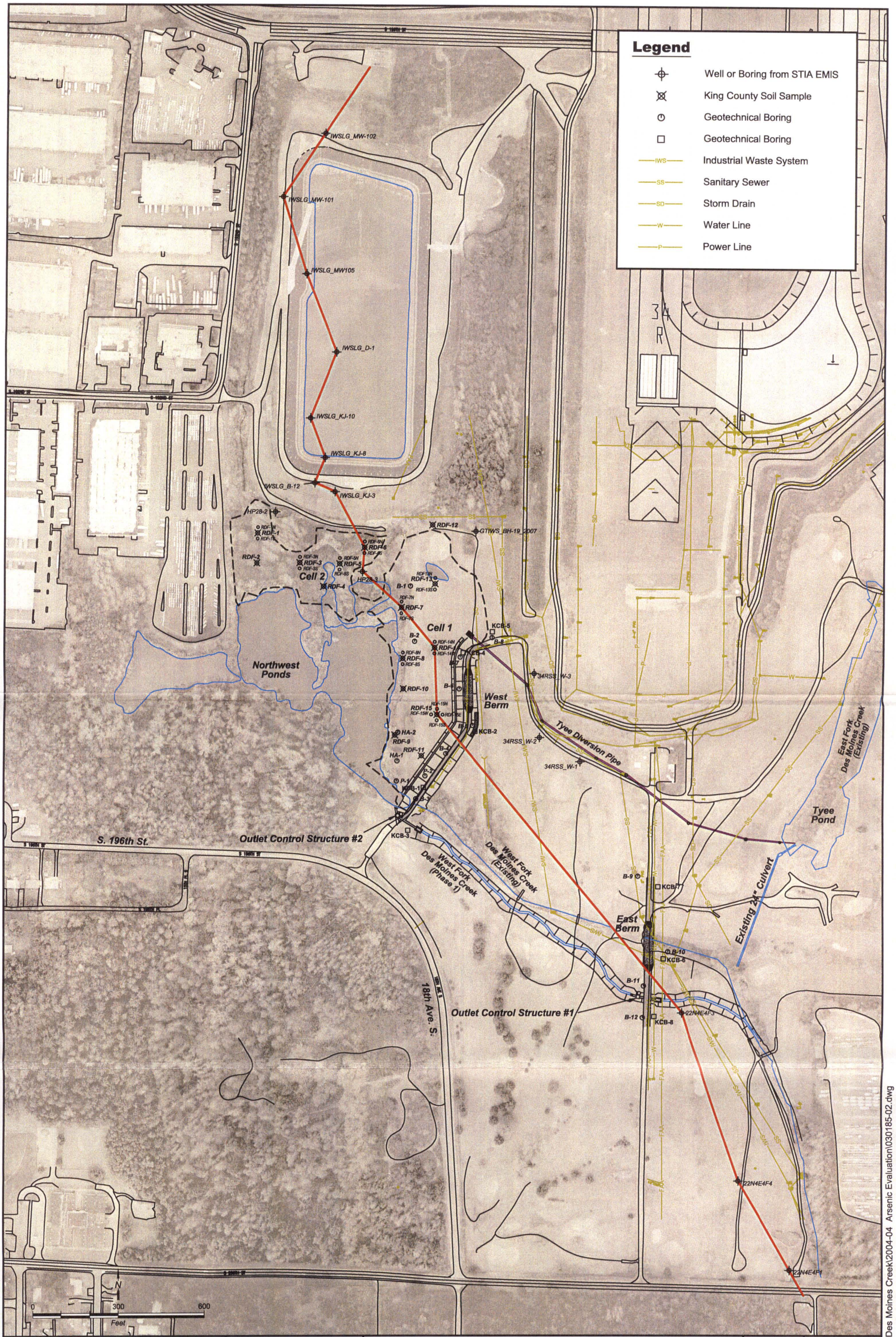

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Project and Borings Map

Des Moines Regional Retention/Detention Facility
SeaTac, Washington

DATE: April 2004	PROJECT NO. 030185
DESIGNED BY: JSL	
DRAWN BY: SDM/PMB	FIGURE NO. 2
REVISED BY: PMB	

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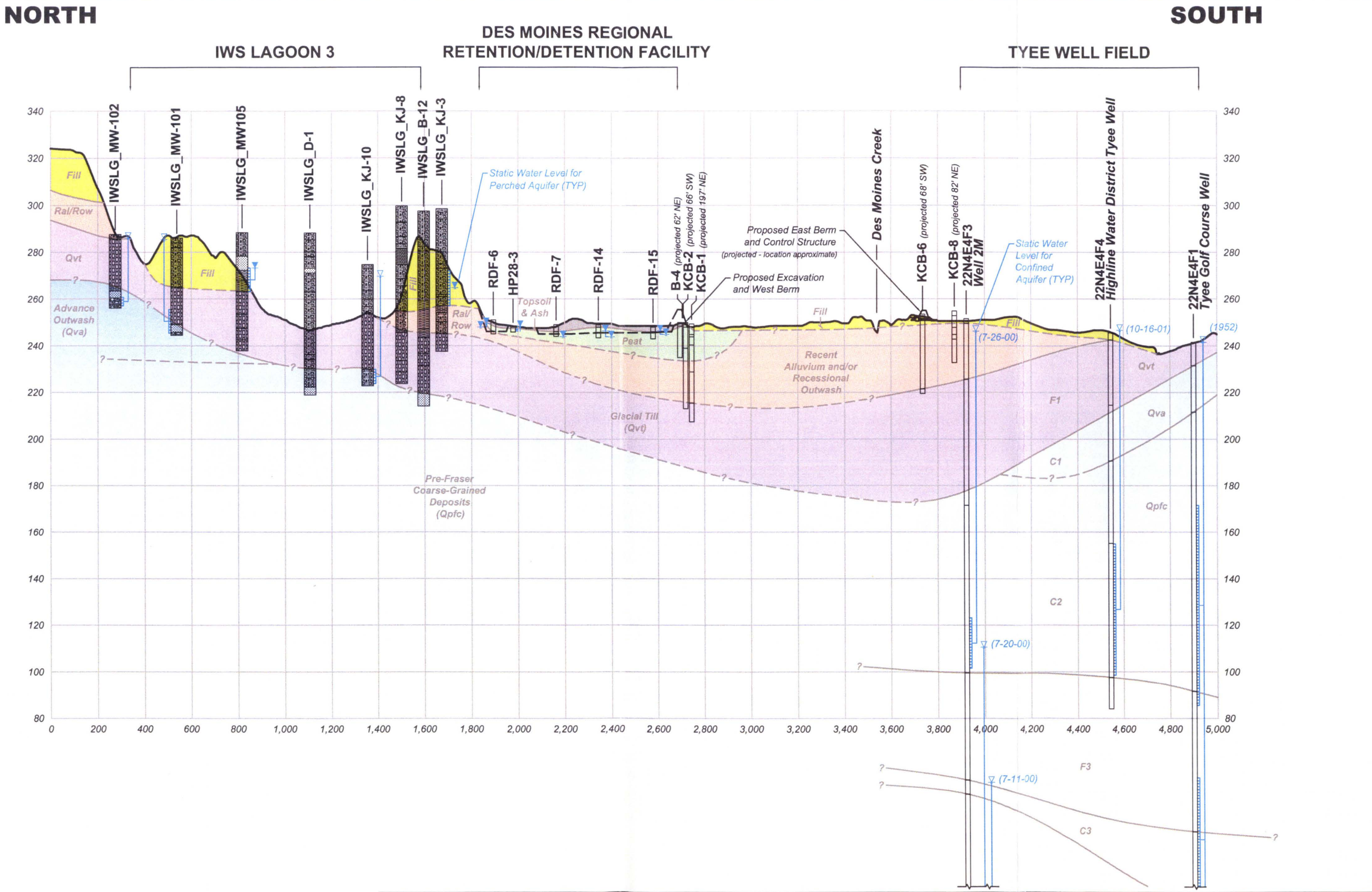

$\Sigma^2\Pi$ S. S. Papadopulos & Associates, Inc.	GREGORY L. GLASS Environmental Consultant 8315-B Fifth Avenue NE Seattle, Washington 98115	Aspect consulting IN-DEPTH PERSPECTIVE 179 Madrone Lane North, Bainbridge Island, WA 98110, (206) 780-9370 811 First Avenue #480, Seattle, WA 98104, (206)-328-7443	**Regional Geologic Cross Section** Des Moines Regional Detention/Retention Facility SeaTac, Washington	DATE: April 2004 DESIGNED BY: JJS/JSL DRAWN BY: SDM REVISED BY: PMB	PROJECT NO. 030185 FIGURE NO. 3

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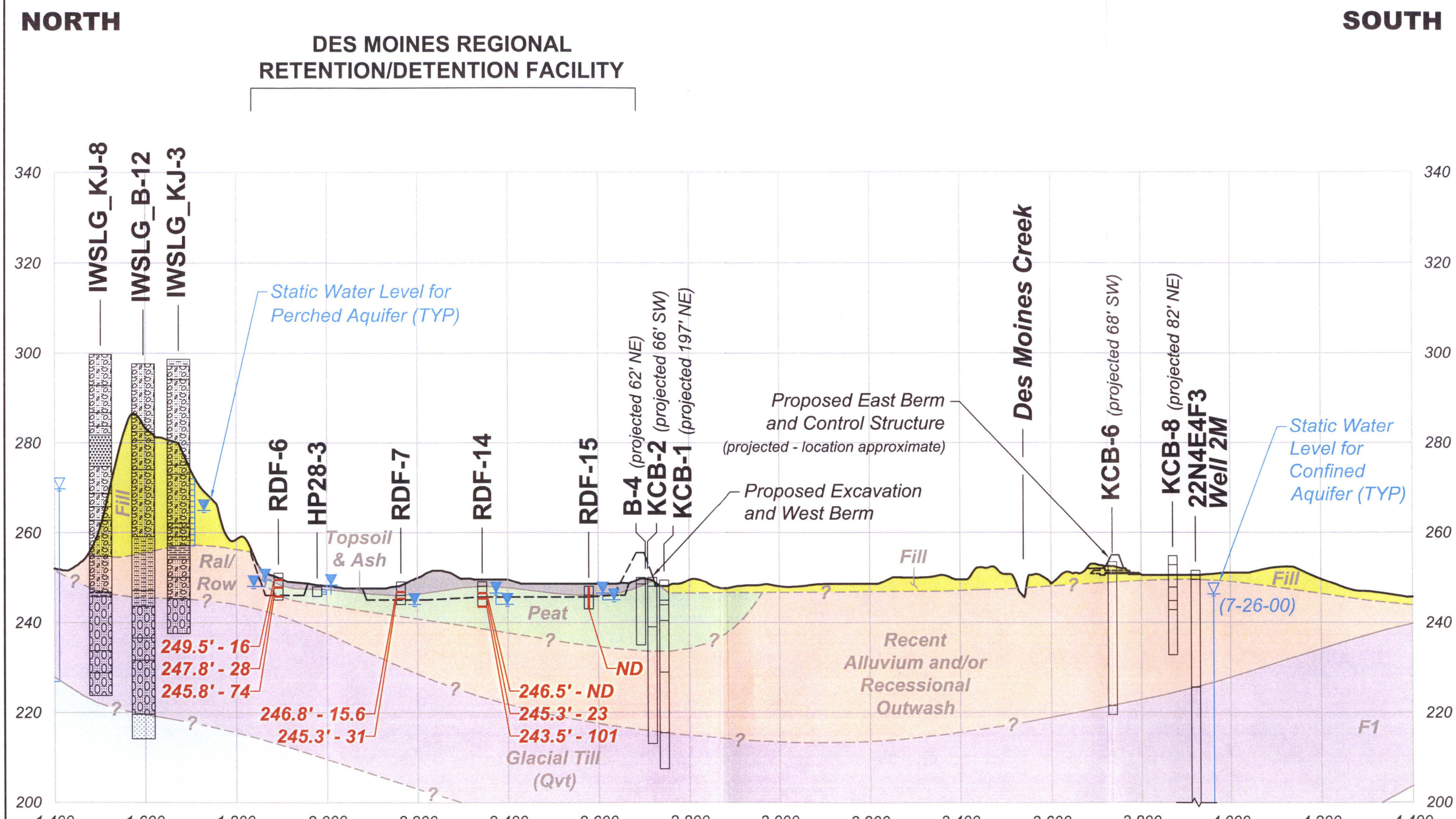

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Geologic Cross Section Detail
Existing Grade
Des Moines Regional Detention/Retention Facility
SeaTac, Washington

DATE:	April 2004	PROJECT NO.	030185
DESIGNED BY:	JJS/JSL		
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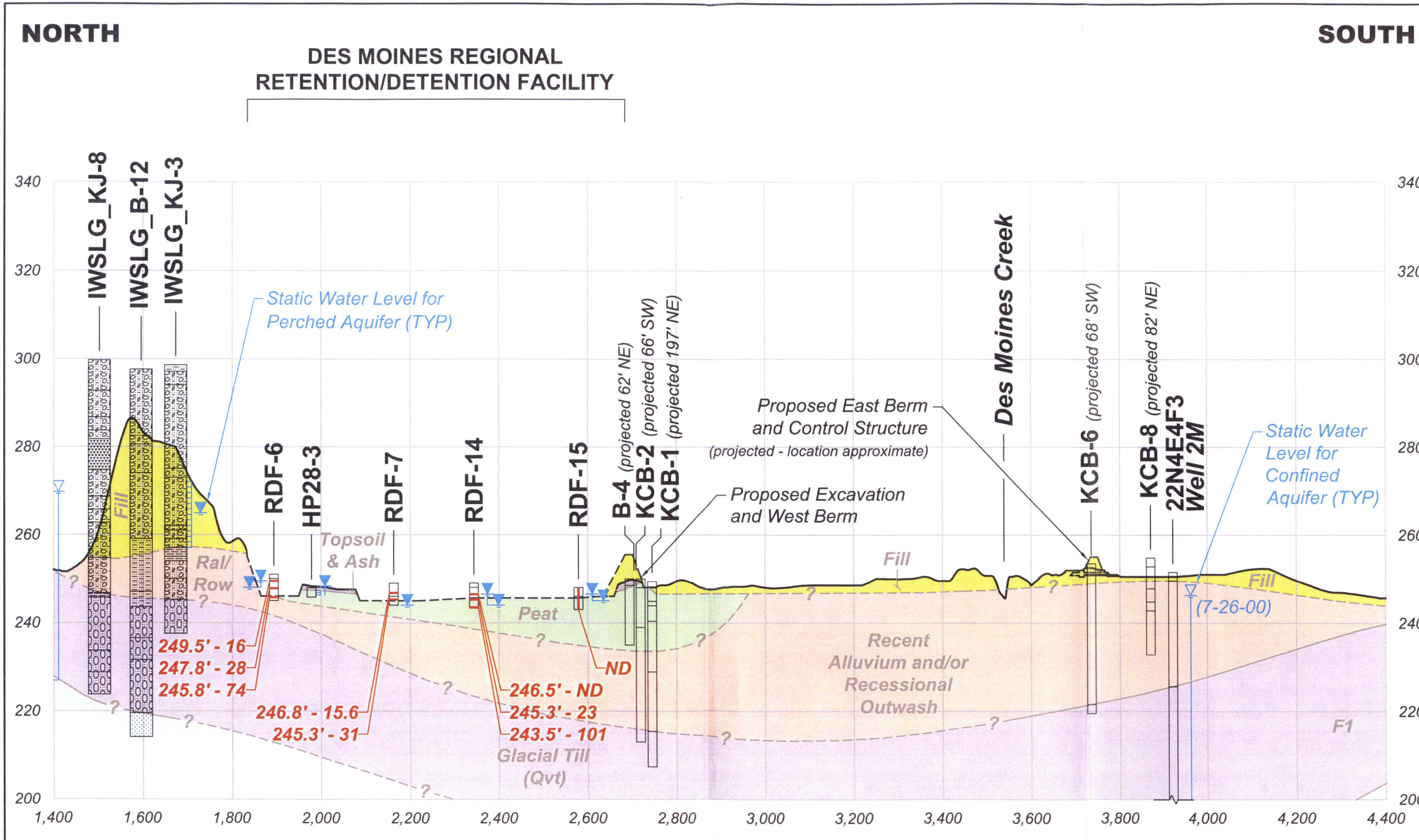

Σ²Π S. S. Papadopulos & Associates, Inc.	Aspect consulting IN-DEPTH PERSPECTIVE 179 Madrone Lane North Bainbridge Island, WA 98110 (206) 780-9370 · 811 First Avenue #480 Seattle, WA 98104 (206)-328-7443	**Geologic Cross Section Detail** **Proposed Grade** Des Moines Regional Detention/Retention Facility SeaTac, Washington	DATE: April 2004 DESIGNED BY: JJS/JSL DRAWN BY: SDM REVISED BY: PMB	PROJECT NO. 030185 FIGURE NO. 5

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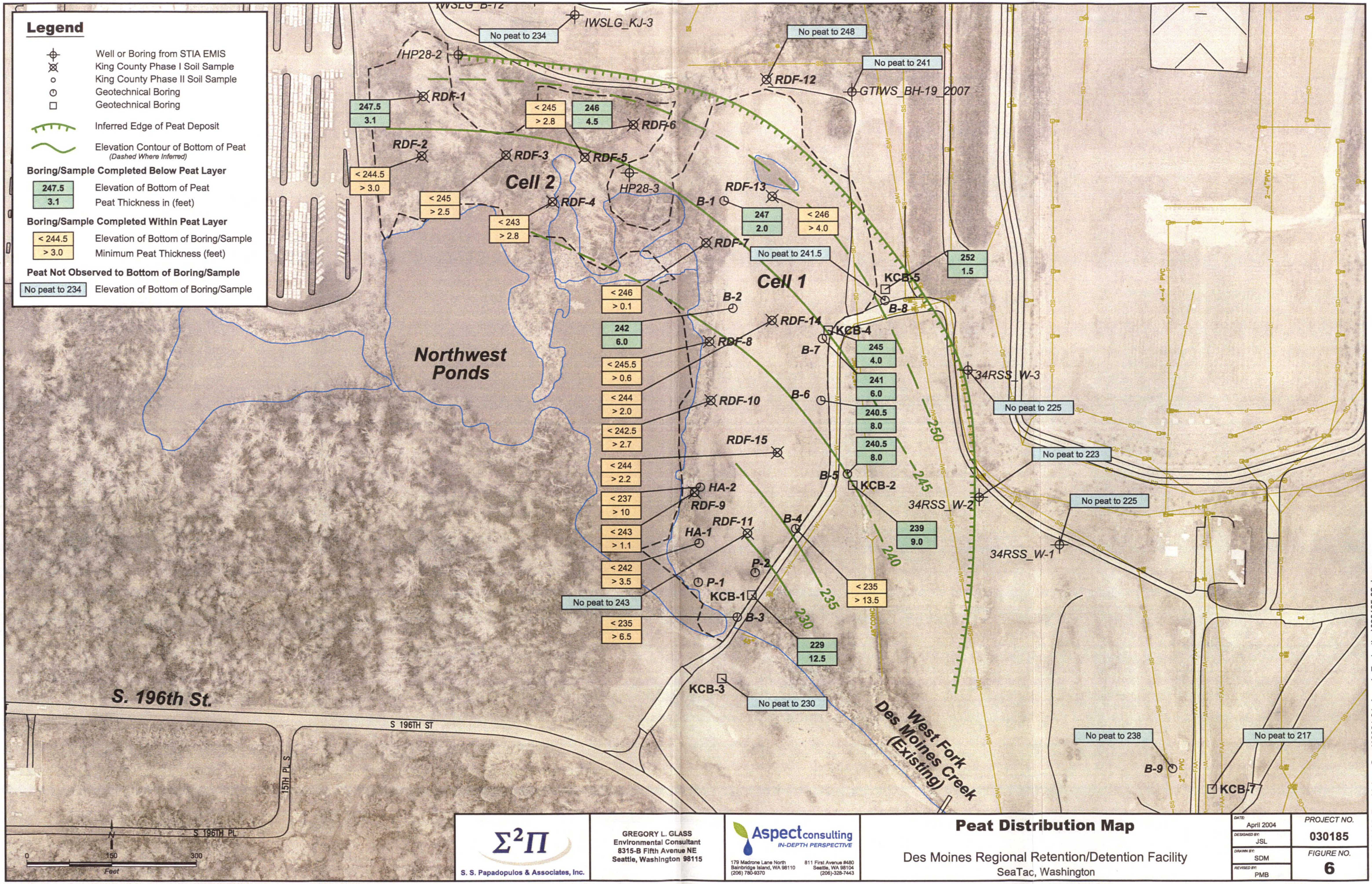
Legend
Well or Boring from STIA EMIS
King County Phase I Soil Sample
King County Phase II Soil Sample
Geotechnical Boring
Geotechnical Boring
Inferred Edge of Peat Deposit
Elevation Contour of Bottom of Peat
(Dashed Where Inferred)
Boring/Sample Completed Below Peat Layer
247.5 Elevation of Bottom of Peat
3.1 Peat Thickness in (feet)
Boring/Sample Completed Within Peat Layer
< 244.5 Elevation of Bottom of Boring/Sample
> 3.0 Minimum Peat Thickness (feet)
Peat Not Observed to Bottom of Boring/Sample
No peat to 234 Elevation of Bottom of Boring/Sample
Cell 2
Cell 1
Northwest Ponds
S. 196th St.
S 196TH ST
S 196TH PL
15TH PL S
West Fork Des Moines Creek (Existing)
IWSLG_KJ-3
No peat to 234
HP28-2
RDF-1
247.5
3.1
< 245
> 2.8
246
4.5
RDF-6
RDF-2
RDF-3
RDF-5
HP28-3
< 244.5
> 3.0
< 245
> 2.5
RDF-4
< 243
> 2.8
No peat to 248
RDF-12
No peat to 241
GTIWS_BH-19_2007
RDF-13
B-1
247
2.0
< 246
> 4.0
RDF-7
No peat to 241.5
252
1.5
KCB-5
B-8
< 246
> 0.1
B-2
242
6.0
RDF-14
KCB-4
RDF-8
< 245.5
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B-7
245
4.0
241
6.0
34RSS_W-3
< 244
> 2.0
RDF-10
B-6
240.5
8.0
No peat to 225
< 242.5
> 2.7
RDF-15
240.5
8.0
No peat to 223
< 244
> 2.2
B-5
KCB-2
HA-2
< 237
> 10
RDF-9
34RSS_W-2
No peat to 225
< 243
> 1.1
RDF-11
HA-1
B-4
239
9.0
34RSS_W-1
< 242
> 3.5
P-2
P-1
< 235
> 13.5
No peat to 243
KCB-1
< 235
> 6.5
B-3
229
12.5
KCB-3
No peat to 230
250
245
240
235
230
No peat to 238
No peat to 217
B-9
KCB-7
0 150 300
Feet
N
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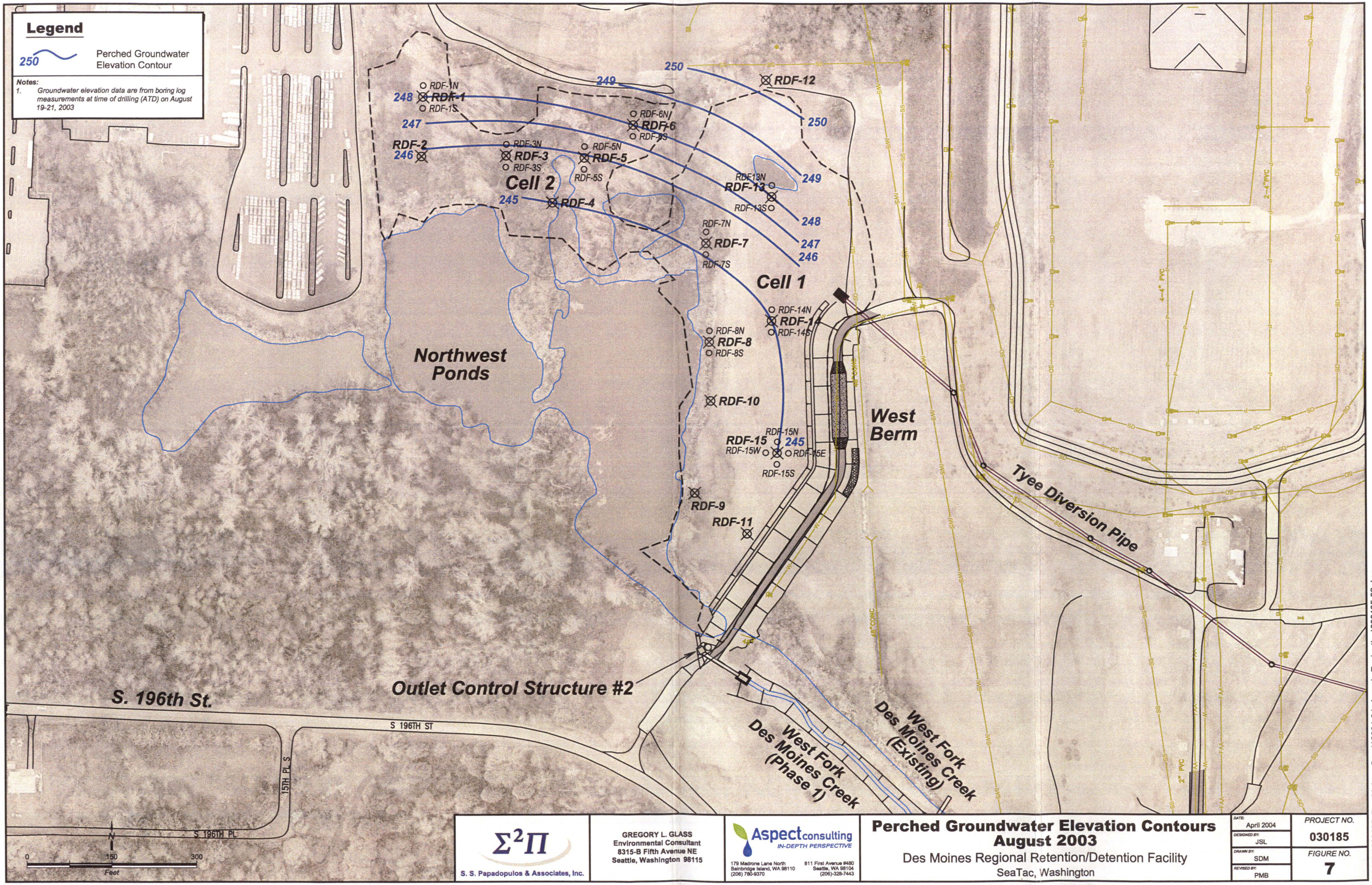
Peat Distribution Map
Des Moines Regional Retention/Detention Facility
SeaTac, Washington
DATE: April 2004
DESIGNED BY: JSL
DRAWN BY: SDM
REVISED BY: PMB
PROJECT NO. 030185
FIGURE NO. 6
Q:\STIA\030185 Des Moines Creek\2004-04 Arsenic Evaluation\030185-02.dwg


Legend
250 Perched Groundwater Elevation Contour
Notes:
1. Groundwater elevation data are from boring log measurements at time of drilling (ATD) on August 19-21, 2003
RDF-1N
RDF-1
RDF-1S
RDF-2
RDF-3N
RDF-3
RDF-3S
RDF-4
RDF-5N
RDF-5
RDF-5S
RDF-6N
RDF-6
RDF-7N
RDF-7
RDF-7S
RDF-8N
RDF-8
RDF-8S
RDF-9
RDF-10
RDF-11
RDF-12
RDF13N
RDF-13
RDF-13S
RDF-14N
RDF-14
RDF-14S
RDF-15N
RDF-15
RDF-15W
RDF-15E
RDF-15S
245
246
247
248
249
250
Cell 2
Cell 1
Northwest Ponds
West Berm
Tyee Diversion Pipe
Outlet Control Structure #2
S. 196th St.
S 196TH ST
15TH PL S
S 196TH PL
West Fork Des Moines Creek (Phase 1)
West Fork Des Moines Creek (Existing)
0 150 300
Feet
Σ²Π
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179 Madrone Lane North Bainbridge Island, WA 98110 (206) 780-9370
811 First Avenue #480 Seattle, WA 98104 (206) 328-7443
Perched Groundwater Elevation Contours
August 2003
Des Moines Regional Retention/Detention Facility
SeaTac, Washington
DATE: April 2004
DESIGNED BY: JSL
DRAWN BY: SDM
REVISED BY: PMB
PROJECT NO. 030185
FIGURE NO. 7
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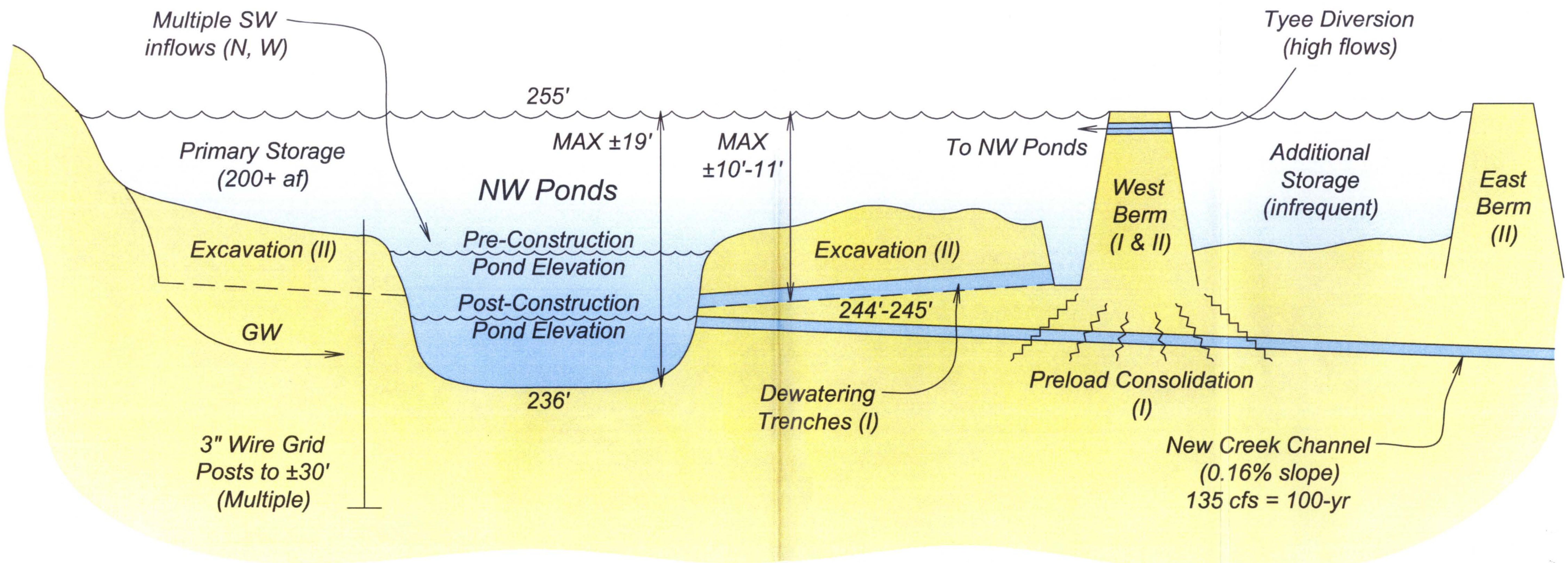
Conceptual Project Diagram



S. S. Papadopulos & Associates, Inc.	GREGORY L. GLASS Environmental Consultant 8315-B Fifth Avenue NE Seattle, Washington 98115	Aspect consulting IN-DEPTH PERSPECTIVE 179 Madrone Lane North Bainbridge Island, WA 98110 (206) 780-9370 811 First Avenue #480 Seattle, WA 98104 (206)-328-7443	**Conceptual Project Diagram** Des Moines Regional Detention/Retention Facility SeaTac, Washington	DATE: April 2004 DESIGNED BY: JJS/JSL DRAWN BY: SDM REVISED BY: PMB	PROJECT NO. 030185 FIGURE NO. 8

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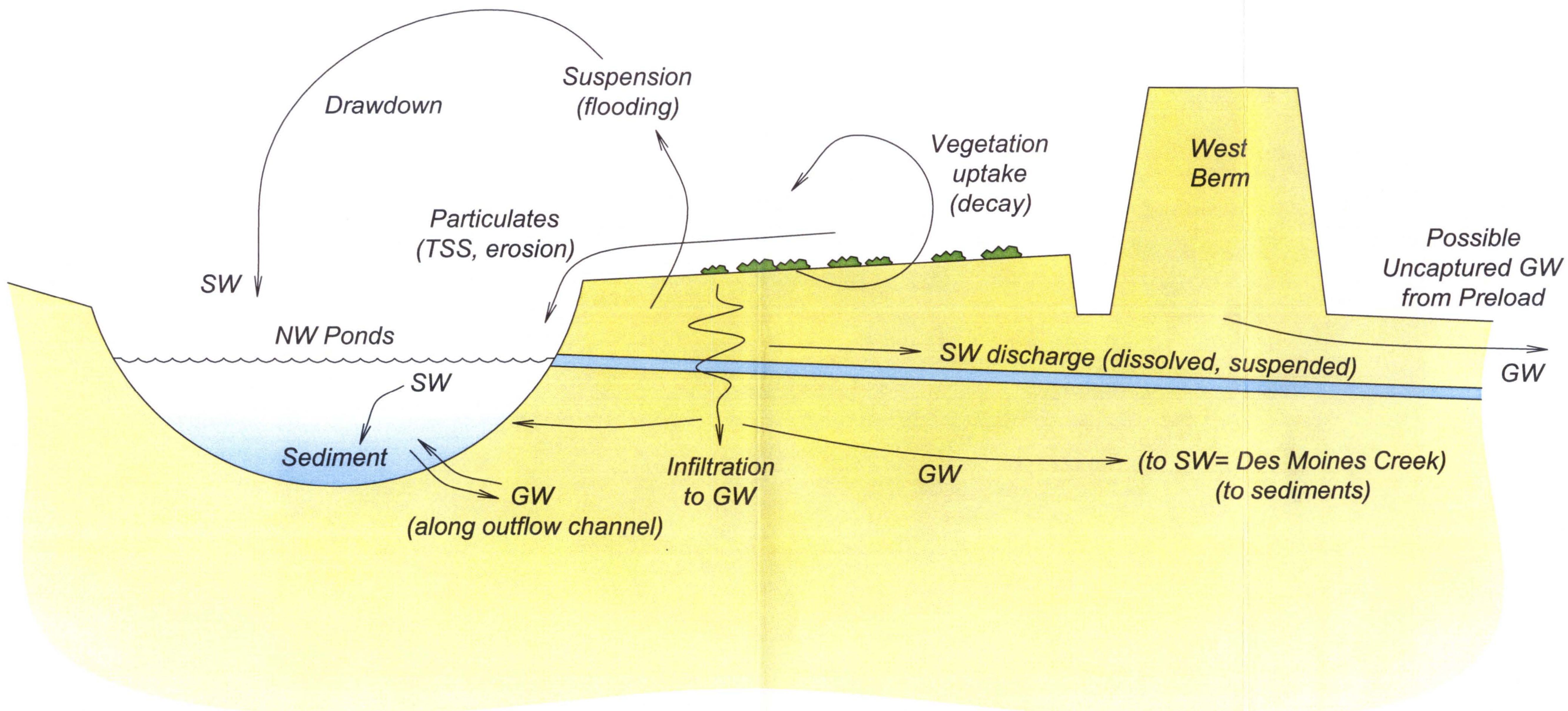
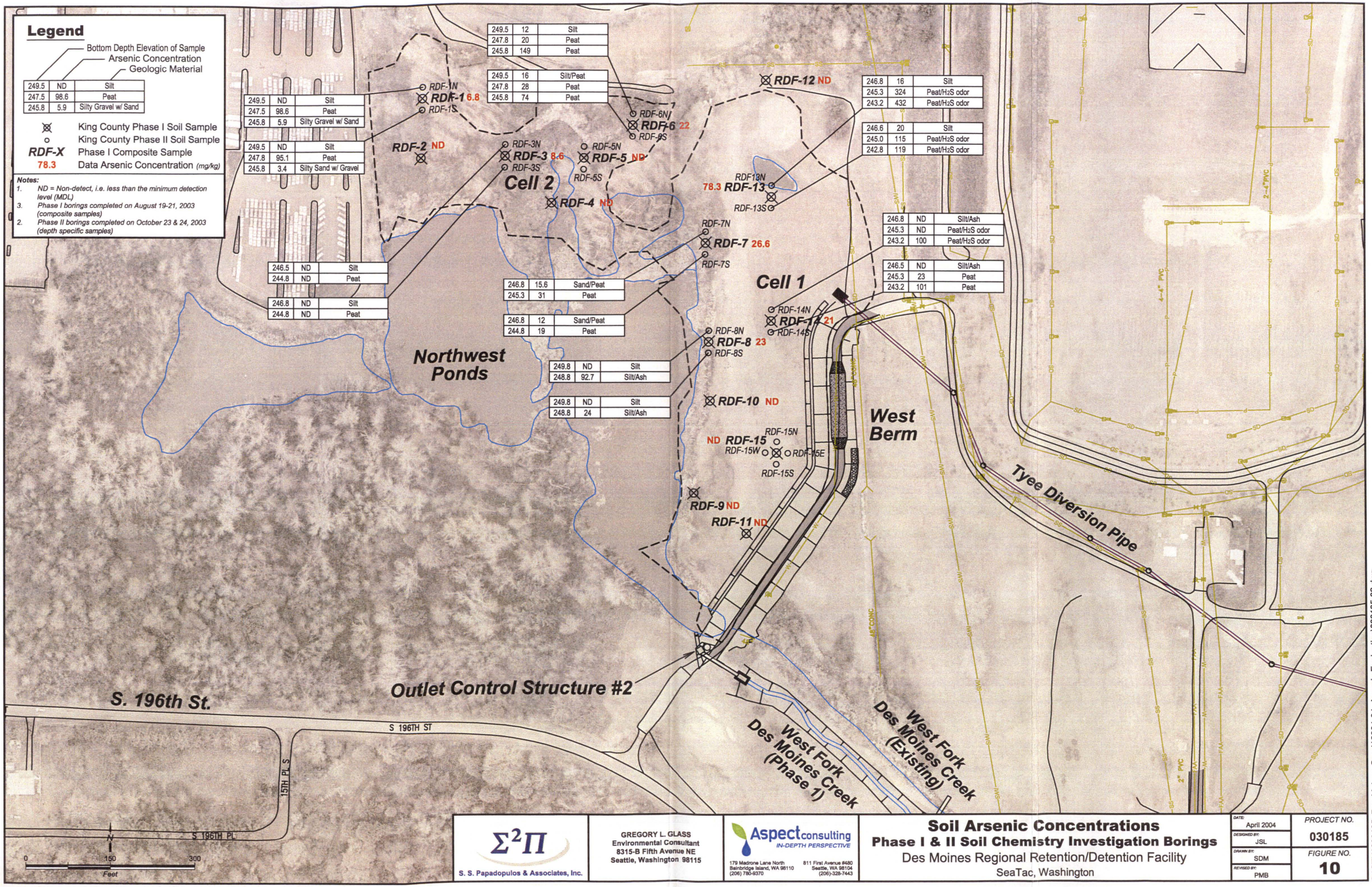
Conceptual Arsenic Pathways



$\Sigma^2\Pi$ S. S. Papadopulos & Associates, Inc.	GREGORY L. GLASS Environmental Consultant 8315-B Fifth Avenue NE Seattle, Washington 98115	Aspect consulting IN-DEPTH PERSPECTIVE 179 Madrone Lane North, Bainbridge Island, WA 98110, (206) 780-9370 811 First Avenue #480, Seattle, WA 98104, (206)-328-7443	**Conceptual Arsenic Pathways** Des Moines Regional Detention/Retention Facility SeaTac, Washington	DATE: April 2004 DESIGNED BY: JJS/JSL DRAWN BY: SDM REVISED BY: PMB	PROJECT NO. **030185** FIGURE NO. **9**

Q:\STIA\030185 Des Moines Creek\2004-04 Arsenic Evaluation\030185-03.dwg



Legend
Bottom Depth Elevation of Sample
Arsenic Concentration
Geologic Material
249.5 ND Silt
247.5 98.6 Peat
245.8 5.9 Silty Gravel w/ Sand
King County Phase I Soil Sample
King County Phase II Soil Sample
RDF-X Phase I Composite Sample
78.3 Data Arsenic Concentration (mg/kg)
Notes:
1. ND = Non-detect, i.e. less than the minimum detection level (MDL)
3. Phase I borings completed on August 19-21, 2003 (composite samples)
2. Phase II borings completed on October 23 & 24, 2003 (depth specific samples)
249.5 12 Silt
247.8 20 Peat
245.8 149 Peat
249.5 16 Silt/Peat
247.8 28 Peat
245.8 74 Peat
249.5 ND Silt
247.5 98.6 Peat
245.8 5.9 Silty Gravel w/ Sand
249.5 ND Silt
247.8 95.1 Peat
245.8 3.4 Silty Sand w/ Gravel
246.8 16 Silt
245.3 324 Peat/H2S odor
243.2 432 Peat/H2S odor
246.6 20 Silt
245.0 115 Peat/H2S odor
242.8 119 Peat/H2S odor
246.8 ND Silt/Ash
245.3 ND Peat/H2S odor
243.2 100 Peat/H2S odor
246.5 ND Silt/Ash
245.3 23 Peat
243.2 101 Peat
246.5 ND Silt
244.8 ND Peat
246.8 ND Silt
244.8 ND Peat
246.8 15.6 Sand/Peat
245.3 31 Peat
246.8 12 Sand/Peat
244.8 19 Peat
249.8 ND Silt
248.8 92.7 Silt/Ash
249.8 ND Silt
248.8 24 Silt/Ash
RDF-1N RDF-1 6.8 RDF-1S
RDF-2 ND
RDF-3N RDF-3 8.6 RDF-3S
RDF-4 ND
RDF-5N RDF-5 ND RDF-5S
RDF-6N RDF-6 22 RDF-6S
RDF-7N RDF-7 26.6 RDF-7S
RDF-8N RDF-8 23 RDF-8S
RDF-9 ND
RDF-10 ND
RDF-11 ND
RDF-12 ND
RDF13N 78.3 RDF-13 RDF-13S
RDF-14N RDF-14 21 RDF-14S
ND RDF-15 RDF-15N RDF-15W RDF-15E RDF-15S
Cell 2
Cell 1
Northwest Ponds
West Berm
Tyee Diversion Pipe
Outlet Control Structure #2
S. 196th St.
S 196TH ST
S 196TH PL
15TH PL S
West Fork Des Moines Creek (Phase 1)
West Fork Des Moines Creek (Existing)
0 150 300 Feet
N
Σ²Π
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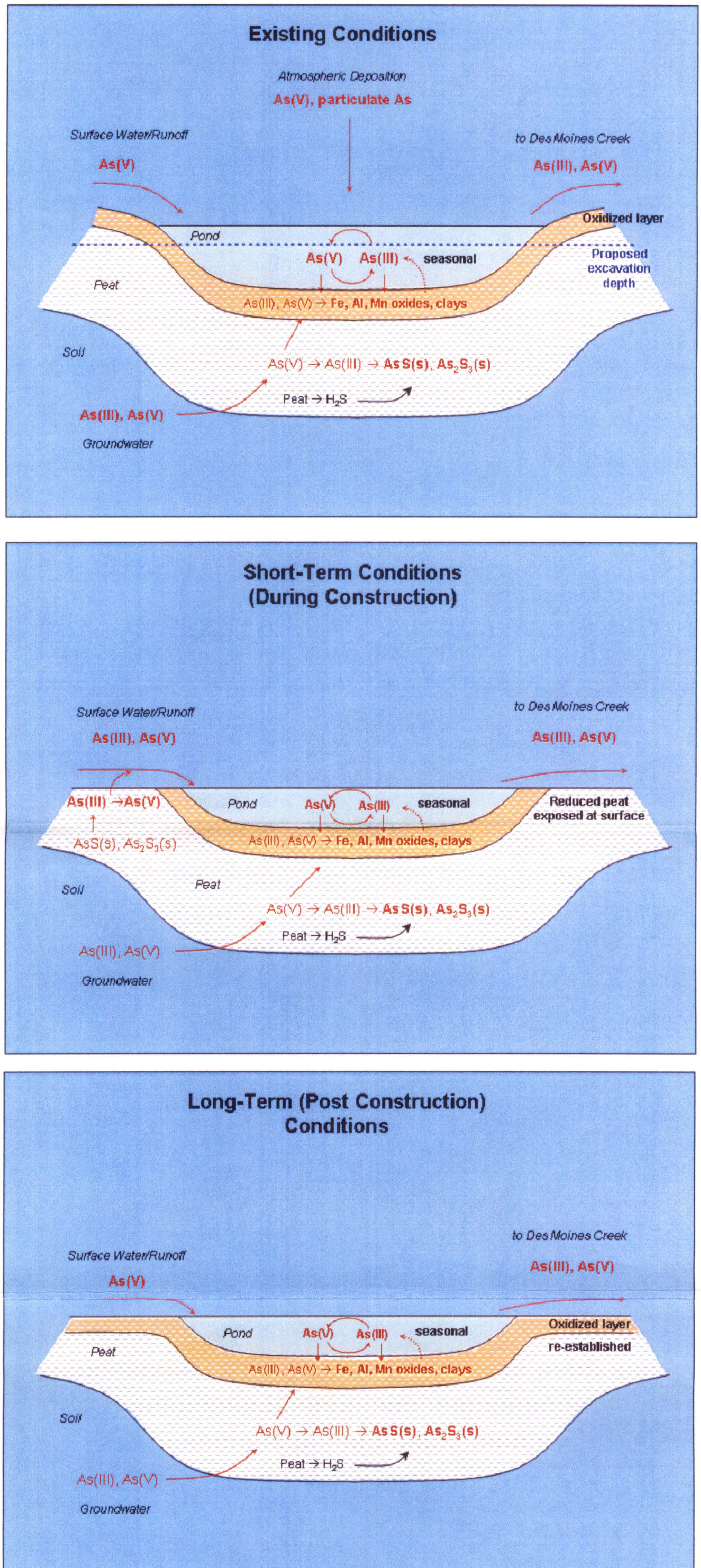
811 First Avenue #480 Seattle, WA 98104 (206)-328-7443
Soil Arsenic Concentrations
Phase I & II Soil Chemistry Investigation Borings
Des Moines Regional Retention/Detention Facility
SeaTac, Washington
DATE: April 2004
DESIGNED BY: JSL
DRAWN BY: SDM
REVISED BY: PMB
PROJECT NO. 030185
FIGURE NO. 10
Q:\STIA\030185 Des Moines Creek\2004-04 Arsenic Evaluation\030185-02.dwg



S. S. Papadopulos & Associates, Inc.	GREGORY L. GLASS Environmental Consultant 8315-B Fifth Avenue NE Seattle, Washington 98115	Aspect consulting IN-DEPTH PERSPECTIVE 179 Madrone Lane North Bainbridge Island, WA 98110 (206) 780-9370 / 811 First Avenue #480 Seattle, WA 98104 (206) 328-7443	**Arsenic Mobility** Des Moines Regional Detention/Retention Facility SeaTac, Washington	DATE: April 2004; DESIGNED BY: JJS/JSL; DRAWN BY: SDM; REVISED BY: PMB	PROJECT NO. 030185; FIGURE NO. 11

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APPENDIX A

Geologic Unit Distribution

A.1 Geology and Stratigraphy

A.1.1 Pre-Fraser Deposits

Pre-Fraser deposits are the deepest and oldest sediments observed in the study area and were identified by their stratigraphic location below known glacial deposits of the Vashon stade of the Fraser glaciation. The Pre-Fraser deposits are subdivided into coarse-grained or fine-grained deposits based on their textural characteristics. These deposits are identified as Qpfc and Qpff, respectively. The coarse and fine deposits exist in multiple layers and no stratigraphic order is implied. Pre-Fraser sediments can be of either glacial or non-glacial origin. Characteristics of non-glacial sediments include the presence of organic matter and wood, the presence of ash or pumice, color changes to darker brown, yellow, or green, an increased degree of interbedding, increased sediment sorting (i.e., more uniform grain size distribution), grain size and an increased proportion of volcanic clast lithologies.

Pre-Fraser Fine-Grained Deposits

Pre-Fraser fine-grained deposits (Qpff) were identified in boring logs in the southeast and southwest portions of the IWS Plant and Lagoon area (about 2,000 feet northwest and northeast of the Northwest Ponds [NWPs]) (AESI, 2000). These units appear to have both glacial and non-glacial origins. The uppermost unit is relatively thick (50 to 100 feet), but laterally discontinuous, and may constitute a regional aquitard where present.

Regional analysis suggests that the uppermost Qpff unit is present under the NWPs, extending laterally about 2,000 feet to the east and 5,000 or more feet elsewhere. This fine-grained unit appears absent along a north-to-south trend that extends south through the eastern side of IWS Lagoon 3 and thence to the confluence of the East and West Forks of Des Moines Creek. The unit is generally absent in the portion of the Des Moines Creek drainage downstream of the confluence.

Pre-Fraser Coarse-Grained Deposits

Coarse-grained Pre-Fraser deposits consist of interbedded sand and gravel with some cobbles, with variable amounts of silt and with silty interbeds. The uppermost pre-Fraser coarse-grained deposits appear to be in the range of 50 to 120 feet thick and are laterally continuous for a radius of at least 10,000 feet from the NWPs. It appears that this uppermost Qpfc layer is in contact with a stratigraphically higher layer of Vashon advance outwash sediments where the Qpff layer is absent Therefore, the confined aquifers in the two coarse units (uppermost Qpfc and the Qva) are hydraulically connected east of the NWPs.

A.1.2 Fraser (Vashon) Glacial Deposits

Glacio-lacustrine Transition Beds
This unit has not been identified in the area around the NWPs.

Advance Outwash
Glacial deposits of the Vashon Stade of the Fraser Glaciation were encountered in the majority of the borings in the study area. The stratigraphically lowest member of these deposits consists of advance glacial outwash (Qva) composed of dense, fine- and medium-grained sand, silty sand, and sand and gravel. Advance glacial outwash is locally extensive, but is absent in an area that appears to include the NWPs and IWS Lagoon 3. The Qva unit directly overlies the uppermost Pre-Fraser fine-grained deposits. Where the fine-grained unit is absent, the Qva layer is in direct contact with the pre-Fraser coarse-grained unit. Where the Qva and Qpfc are in contact, these coarse-grained soils appear to form a regional aquifer that is partially confined below the overlying glacial till in the study area.

Glacial Till
The majority of the monitoring wells and geotechnical borings in the study area encountered glacial till, a very dense, low permeability soil composed of an unsorted to poorly sorted mixture of clay, silt, and sand with variable amounts of gravel. Lenses of stratified sandy and gravely soils are commonly present within the till. These lenses typically have limited lateral extent and may transmit or contain minor amounts of perched groundwater. Regionally, the glacial till is relatively continuous. However, the till appears to be absent in area about 3,000 feet in diameter to the northwest of the NWPs and probably in a similar area to the south. This area is underlain by a pre-Fraser fine-grained unit and therefore a continuous aquitard is expected to exist. The till surface forms a slight bowl that underlies the ponds and Lagoon 3.

Recessional Outwash
Recessional glacial outwash (Qvr), recent alluvium (Qral), and fill (Fill) overlie the glacial till. The Qvr unit consists of medium dense to dense sand, silt, sand with gravel, and silty sand and gravel mixtures. Thin interbeds of silt are common in these generally coarse-grained recessional outwash deposits. Where lacking distinctive characteristics, some recent alluvium and fill may be included within the deposits classified as recessional outwash.

Regionally, recessional outwash is present: (1) as a discontinuous mantle above glacial till in upland areas; and (2) as a much thicker deposit that filled in low-lying areas and recessional meltwater drainage channels. Locally, recessional outwash ranges from absent to perhaps 30 feet thick in the vicinity of the NWPs. Some recent alluvium may be included within deposits classified as recessional outwash in modern-day drainage courses south and west of the lagoons. The hydrogeologic characteristics of the recessional outwash and the coarser portions of recent alluvium units are similar.

A.1.3 Recent Deposits

Recent Alluvium

Recent alluvium (Qal) is unconsolidated detrital material deposited during the post-glacial period by flowing water. Sediments tend to be (uniformly) sorted or semisorted, can either fine or coarse-grained, and are frequently deposited in lakes, streambeds, or wetlands. Recent alluvium, in conjunction with recessional outwash, appears to underlie and surround the peat beds at the Northwest Ponds.

Peat

Peat is a deposit of plant remains in a water saturated environment which is typically formed in a depression on undrained or poorly drained flat lying ground (Rigg, 1958). A peat accumulation rate of about 1 foot in 500 years has been computed in the Puget Sound lowlands (Rigg, 1958). A peat deposit developed post-glacially in the Northwest Pond area and appears to be at least 13.5 feet thick (Figure 6). Soil samples collected by King County describe both a fibrous and an amorphous structure to the peat. A thin layer of volcanic ash was encountered in the King County soil samples of the peat horizon at the Northwest Ponds. This ash layer has been described in other peat localities in the Puget Sound region and represents fallout from historic volcanic eruptions (Rigg, 1958). The formation of the NWPs is a result of commercial mining extraction/excavation of that peat, circa 1960. The remaining peat layer appears to vary from 2 to 15 feet in thickness.

Fill

Fill is the uppermost stratigraphic soil in most of the study area. Because of the nature of fill soils, many possible combinations of grain size and density or consistency are possible. If fill is not identified as such on the original soil log, it is typically difficult to distinguish from natural soils. Identified fill soils consist of silty sand with gravel, silty gravelly sand, silty sand, and sand.

Fill in the study area is present as a result of agriculture in the current Northwest Pond area and grading activities for the IWS treatment plant and the Tyee Golf course, the IWS lagoons, and the airport runway. Identified fill thickness ranged from near zero up to 30 feet in the embankment for Lagoons 3. Fill may be up to 55 feet thick in the area of the borings and wells south of Lagoon 3.

APPENDIX B

Environmental Geochemistry of Arsenic

B.1 Arsenic Speciation

The chemical form or speciation of dissolved arsenic is important in determining how strongly it reacts with solid phases and surfaces and therefore the mobility of arsenic in natural systems. Arsenic can occur in a number of oxidation states, including +5, +3, 0, -3, and can be transformed from one state to another in response to changes in environmental conditions.

In natural waters, inorganic chemical species with the +3 (As(III) or arsenite) and +5 (As(V) or arsenate) oxidation states tend to dominate. Organic arsenic forms also occur, mostly in surface waters where they are produced by biological activity, or as a result of industrial pollution. Figure B-1 shows the equilibrium distribution of dissolved As(V) and As(III) species as a function of Eh (oxidation-reduction potential) and pH. Oxidizing conditions are characterized by higher values of Eh indicate and reducing conditions are typified by lower (more negative) values. As(V) species are stable under oxidizing conditions whereas As(III) species are stable under reducing conditions. In the pH range typical of most natural waters and soils, As(V) exists as a negatively charged anion (H2AsO4- or HAsO4--), whereas As(III) is uncharged (H3AsO3).

Some microbial organisms (e.g., bacteria, algae) can convert ingested inorganic arsenic species to organic species such as monomethylarsonic (MMA) and dimethylarsinic (DMA) acids as a means of detoxification (Anderson and Bruland, 1981; Cullen and Reimer, 1989; Huysmans and Frankenberger, 1991; Hasegawa et al., 2001; Hellweger et al., 2003). Organic arsenic concentrations in surface waters vary seasonally and are correlated with algal blooms.

In the presence of sulfide, soluble thioarsenite species are known to form (Eary, 1992; Helz et al., 1995; Wood et al., 2002; Wilkin et al., 2003). Although the exact nature of these complexes remains unclear, such species can be the dominant form of dissolved arsenic under sulfate-reducing conditions.

B.2 Processes Controlling Arsenic Fate & Transport

B.2.1 Mineral-Water Interactions

Mineral-water interactions can be divided into two broad types from a geochemical point of view: precipitation-dissolution reactions and adsorption-desorption reactions. Precipitation-dissolution reactions involve the growth or erosion of a mineral structure and so only involve those elements included in the chemical formula of the mineral.

Adsorption-desorption reactions involve the binding of a dissolved substance to the surfaces of minerals (or other solids). The adsorption isotherm relates the concentration of a chemical in solution to its concentration on a surface. Generally, the greater the concentration of a chemical in solution, the greater its concentration bound to the surface. These reactions tend to reach equilibrium relatively rapidly. The actual concentration on the surface depends on how strongly the chemical binds to the surface and the concentrations of other chemicals which can bind to the surface and thereby compete for the available surface binding sites. The amount of a particular chemical adsorbed may therefore be very sensitive to the concentration of other chemicals present in the water.

Dissolved As interacts strongly with many mineral surfaces (iron (hydr)oxides, manganese and aluminum oxides, clay minerals) and natural organic matter (e.g. peat) (Xu et al, 1988, 1991; Belzile and Tessier, 1990; Fuller et al, 1993; Waychunas et al., 1993, 1995; Bowell, 1994; Kuhlmeier, 1997; Chiu and Hering, 2000; Goldberg and Johnson, 2001; Lin and Puls, 2001; Hansel et al., 2002; Dixit and Hering, 2003; Farquhar et al., 2003; Saada et al., 2003). As(V) is generally adsorbed more strongly than As(III) (Manning et al., 1998; Raven et al., 1998; Manning and Suarez, 2000; Dixit and Hering, 2003). Adsorption is pH-dependent, and decreases at low and high pH (Xu et al., 1988, 1991; Dixit and Hering, 2003). Adsorption may be further reduced if competing ions such as phosphate and silicate are present (Manning and Goldberg, 1996a,b; Goldberg, 2002; Smith et al., 2002).

Coprecipitation is also a common natural process whereby arsenic can be incorporated or scavenged into a mineral structure as it forms, e.g. arsenic can be coprecipitated during the formation of pyrite (Rittle et al., 1995). Also, both phosphate and arsenic are coprecipitated during the formation of iron oxides (Ford, 2002; Caetano et al., 2002).

Precipitation-dissolution and adsorption-desorption reactions are not entirely unrelated processes, and in practice the distinction is not always that clear. For example, As(III) which forms highly insoluble arsenic-sulfide minerals will tend to adsorb strongly to other sulfide minerals such as pyrite, FeS2 (Bostick and Fendorf, 2002) .

In the presence of extremely high concentrations of reduced sulfur, dissolved thioarsenite species can be significant. Reducing, acidic conditions favor precipitation of orpiment (As2S3), realgar (AsS) or other sulfide minerals containing coprecipitated arsenic (Moore et al., 1988; Schaulfelberger, 1994; Rittle et al., 1995; McCreadie et al., 2000). High arsenic waters are not expected where concentrations of free sulfide are high. except at alkaline pH (>7) where thioarsenite species will be more important.

B.2.2 Redox Transformations

Redox potential (Eh) and pH are the most important factors controlling arsenic speciation and mobility. Under the appropriate conditions, As(III) can be oxidized to As(V) (Ghurye et al., 2001). Conversely, As(V) can be reduced to As(III). Although the rates of such abiotic redox reactions can be slow under ambient conditions, their rates can be greatly increased through the involvement of biological organisms (Brannon et al., 1987; Jackson et al., 2003; Oremland and Stolz, 2003; Macur et al, 2004).

In the presence of reductants such as organic matter, iron oxides can be reductively dissolved, releasing the adsorbed As to water. As(V) can also be reduced to As(III) by organic matter or sulfide (Langner and Inskeep, 2000). There are also arsenate-respiring bacteria which reduce As(V) through a dissimilatory metabolic process. These bacteria have been found to play an important role in mobilizing arsenic in many surface water and sediment environments (Dowdle et al., 1996; Ahmann et al., 1997; Newman et al., 1997; Blum et al., 1998; Zobrist et al., 2000; Hoeft et al., 2002; Kneebone et al., 2002; Santini et al., 2002; Afkar et al., 2003).

As(III) can be oxidized to As(V) by dissolved oxygen, nitrate, manganese oxides, ferric iron, and these transformations are also microbially mediated (Senn and Hemond, 2002; Salmassi et al., 2003).

Under sulfate-reducing conditions, As(III) can form insoluble precipitates such as realgar and orpiment. These As sulfides are not stable under oxidizing conditions and will oxidize in the presence of oxygen with release of As(V) and sulfate to solution (Lengke and Tempel, 2002, 2003).

B.2.3 Kinetics of Transformation Reactions

Kinetics refers to the speed of chemical reactions. In contrast to adsorption-desorption reactions, which are generally rapid enough to be described as equilibrium reactions in natural waters, redox transformations of arsenic tend to proceed more slowly. Equilibrium thermodynamic calculations predict that As(V) should dominate over As(III) in all but strongly reducing conditions (Figure B-1). However, such theoretical behavior is not always observed in natural waters (Eary and Schramke, 1990; Kuhn and Sigg, 1993). The production of As(III) in surface waters is attributed to biological transformations. Subsequent oxidation of As(III) by dissolved oxygen is particularly slow, with a half-life on the order of several months to a year (Johnson and Pilson, 1975).

Laboratory studies show that the kinetics of nonbiological oxygenation of As(III) are slowest in the slightly acid range, around pH 5. Eary and Schramke (1990) suggested that the half-life for As(III) in natural waters is 1–3 years although the rate may be greater if manganese oxides are present. There is ample evidence that the rate of As(III) oxidation is increased in the presence of manganese-oxide particles with half-lives being reduced to as little as 10–20 min (Oscarson et al., 1981; Scott and Morgan, 1995). The rate of oxidation is independent of the concentration of dissolved oxygen, being controlled by the rate of a surface reaction. Photochemical oxidation and reduction may be additional factors in surface waters.

Both the oxidation of As(III) and the reduction of As(V) can be bacterially catalyzed. Wilkie and Hering (1998) found that As(III) in geothermal waters discharging to streams in California was oxidized rapidly downstream (calculated half-life as little as 0.3 hours), due to bacterial involvement. T he reduction of As(V) to As(III) in Mono Lake was also catalyzed by bacteria (half-life ranging from 2 to 30 days, Oremland et al., 2000). Methylated As species are also readily oxidized chemically and biologically.

Less is known about the rate of solid-phase reduction of As(V) to As(III) but studies with soils and sediments provide some evidence. Under moderately reducing conditions (Eh < 100 mV) induced by flooding, As(V) is reduced to As(III) in a matter of days to several weeks and adsorbed As(V) is released as As(III) (Masscheleyn et al., 1991; Reynolds et al., 1999). Masscheleyn et al. (1991) found from laboratory experiments that some of the As was released before Fe, implying reductive desorption from iron oxides rather than reductive dissolution. Up to 10 percent of the total As in the soil eventually became soluble in that study. Smith and Jaffé (1998) found that As(V) reduction in benthic sediments could be modeled as a first order reaction with respect to As(V) with a half life of ~2 days.

B.3 Biogeochemical Cycling

In surface waters, As(V) is generally the dominant species, although significant seasonal variations in speciation as well as absolute concentration have been found (Spliethoff et al., 1995; Harrington et al., 1998; Knauer et al., 2000; LaForce et al., 2000; Takahashi et al., 2004). Concentrations and relative proportions of As(V) and As(III) vary according to changes in input sources, redox conditions and biological activity. The presence of As(III) may be maintained in oxic waters by biological reduction of As(V), particularly during summer months.

Proportions of As(III) and As(V) are particularly variable in stratified lakes where redox gradients can be large and seasonally variable (Kuhn and Sigg, 1993). Distinct changes in arsenic speciation occur in lake water profiles as a result of redox changes. For example, in the stratified, hypersaline and hyperalkaline Mono Lake (California, USA), there is a predominance of As(V) in the upper oxic layer and of As(III) in the lower reducing layer. Rapid oxidation of As(III) occurs during the early stages of lake turnover as a result of microbial activity (Oremland et al., 2000).

Unlike Mono Lake, speciation of As in lakes does not necessarily follow that expected from thermodynamic considerations. Recent studies have shown that As (III) predominates in the oxidized epilimnion of some stratified lakes while As (V) may persist in the anoxic hypolimnion (Kuhn and Sigg, 1993; Newman et al., 1998). Proportions of arsenic species may also vary according to the availability of particulate iron and manganese oxides (Pettine et al., 1992; Kuhn and Sigg, 1993).

Organic forms of arsenic are usually minor in surface waters. In lake waters from Ontario, Azcue and Nriagu (1995) found As(III) concentrations of 7–75 micrograms per liter (μg/L), As(V) of 19–58 μg/L and only 0.01–1.5 μg/L of organic As species.

Nonetheless, proportions of organic forms of arsenic can increase as a result of methylation reactions catalyzed by microbial activity (bacteria, yeasts, algae). The dominant organic forms found are DMA and MMA, where As is present in both cases in the +5 oxidation state. Proportions of these two species have been noted to increase in summer as a result of increased microbial activity (e.g., Hasegawa, 1997). The organic species may also be more prevalent close to the sediment-water interface (Hasegawa et al., 1999).

In groundwaters, the ratio of As(III) to As(V) can vary enormously as a result of large variations in aquifer redox conditions, redox gradients and history. In strongly reducing aquifers (iron- and sulfate-reducing conditions), As(III) typically dominates. Concentrations of organic forms are generally low or negligible in groundwaters (e.g., Chen et al., 1995).

As with most trace metals, the concentration of arsenic in natural waters is probably normally controlled by some form of solid-solution interaction. This is the case for soil solutions, pore waters and groundwaters where the solid/solution ratio is large but it is also often the case in surface waters (lakes and reservoirs) where the concentration of solid particles is small but still significant. In these open bodies, the particles can be of mineral and biological origin. It is likely that in most soils and aquifers, mineral-As interactions are likely to dominate over organic matter-As interactions, although organic matter (peat) may interact to some extent through its reactions with the surfaces of minerals.

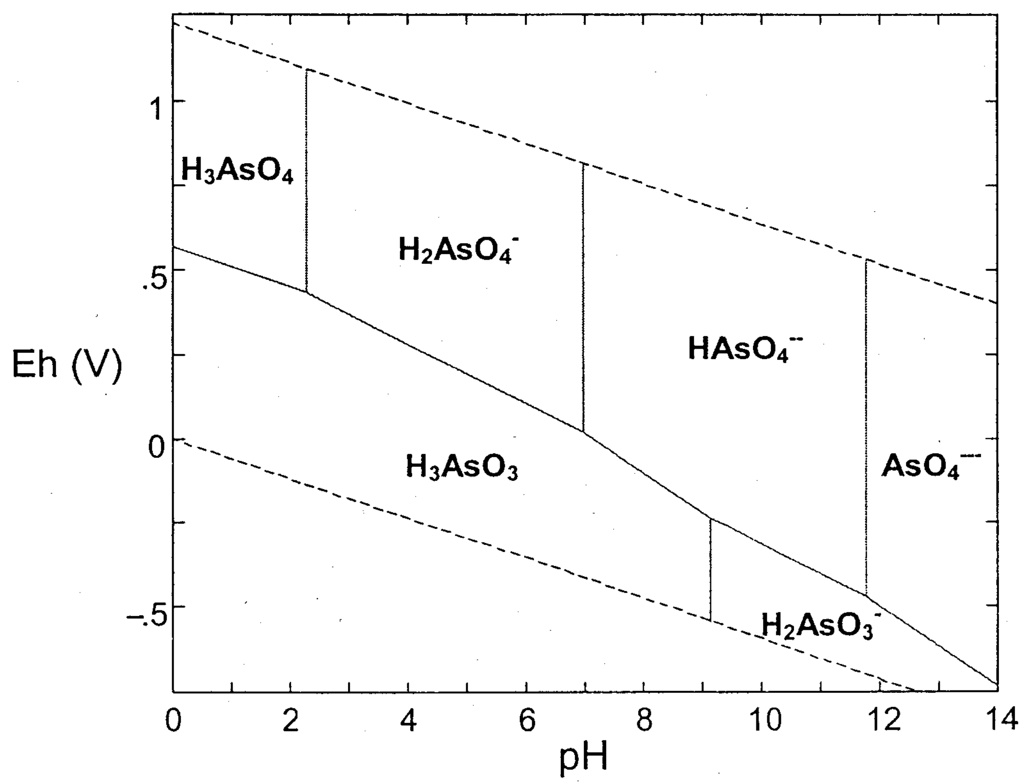

Figure B-1 - Eh-pH diagram showing stability fields of dissolved arsenic species

B.4 Arsenic References

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