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Coal Combustion Waste Disposal Facility Design: Electric Power Cooperative Selby, South Dakota

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COAL COMBUSTION WASTE DISPOSAL FACILITY DESIGN: ELECTRIC POWER COOPERATIVE SELBY, SOUTH DAKOTA

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as a Geological Engineering Design Project

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EXECUTIVE SUMMARY

A rural electric cooperative (REC) proposes to build a 700 megawatt (MW) coal fired base load electrical generating station in north-central South Dakota. The plant would consist of a supercritical pulverized coal boiler and a steam turbine generator. Solid wastes generated through the operation of the boiler and associated plant air pollution control systems would be disposed at an onsite landfill. A 202-acre landfill with 10 percent slopes is proposed to manage approximately 685 tons of waste each day; a design capacity of 15,000,000 yd^3 is required for the anticipated 50-year life of the facility. The objective of this report is to provide an engineering design for a solid waste landfill that is environmentally sound and economically feasible.

The design considers project site background information (soils, geology, and climate) and the regulatory requirements set forth in the State of South Dakota solid waste management rules. A variety of landfill liner, leachate collection, and cover system options were evaluated using the US EPA Hydrologic Evaluation of Landfill Performance (HELP) model. The HELP computer program is a hydrologic model of water movement across, into, through and out of landfills. A 24 in. thick compacted clay liner (CCL), a 48 in. thick CCL, and a composite liner consisting of a 60 mil high density polyethylene (HDPE) geomembrane overlying a compacted soil layer were evaluated with and without a leachate collection system. Two cover systems were evaluated to predict the performance of the closed landfill. Again, the HELP model was used to determine the predicted seepage rate through both 36 in. thick and 48 in. thick landfill cover systems and through the entire landfill. An economic evaluation of the various design options is also provided. The recommended design includes a 48 in. thick composite cover system and a 24 in. thick CCL bottom liner at a total estimated cost of \$41,301 per acre.

At present, no site specific hydrogeologic information is available; important characteristics such as hydraulic conductivity and hydraulic gradient are not known. Calculations using a range of aquifer parameters and the gradients were completed to provide an envelope of contaminant travel time values. The US EPA Optimal Well Locator (OWL) program was used to account for the effects of dispersion in determining the lateral spacing of wells.

Based on the hypothetical landfill layout and groundwater flow regime depicted in this design study, the recommended monitoring network for the 202-acre site consists of 16 wells. Six wells would be either up- or side-gradient, while ten wells would be positioned down-gradient. Downgradient wells would have a lateral spacing of approximately 70 m and would be located a maximum of 25 m from the landfill boundary. Calcium, sodium, boron, sulfate, bicarbonate and chloride are recommended as "indicator" parameters for the long-term monitoring of groundwater at the facility.

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ACKNOWLEDGMENTS

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Lastly, I thank my wife, Tamara, for her support and patience during my pursuit of a Geological Engineering Degree.

INTRODUCTION

A rural electric cooperative (REC) is proposing to build a 700 megawatt (MW) coal-fired base-load electrical generating station in north-central South Dakota (SD). Figure 1 illustrates the location of the project, located in Walworth County, approximately three miles west of the town of Selby. The plant would consist of a supercritical pulverized coal boiler and a steam turbine generator powered by Powder River Basin (PRB) sub-bituminous coal. Solid waste generated through the operation of the boiler and plant air pollution control systems would be disposed at an onsite landfill.

PROBLEM DEFINITION AND OBJECTIVE

The long-term disposal of any waste material in a landfill poses several potential problems, including the contamination of soil, groundwater and surface water by leachate movement out of the landfill. The purpose of this report is to provide a design for an environmentally sound and economically viable solid waste landfill. The design takes into account site characteristics such as soils, geology, and climate, and is consistent with the Administrative Rules of South Dakota.

BACKGROUND INFORMATION

Air Pollution Control Equipment

The proposed plant would use state-of-the-art air pollution control equipment, consisting of nitrogen oxide (NO_x), particulate, sulfur dioxide, and mercury control systems. NO_x control would be achieved through the use of low NO_x burners, over-fire air, and selective catalytic

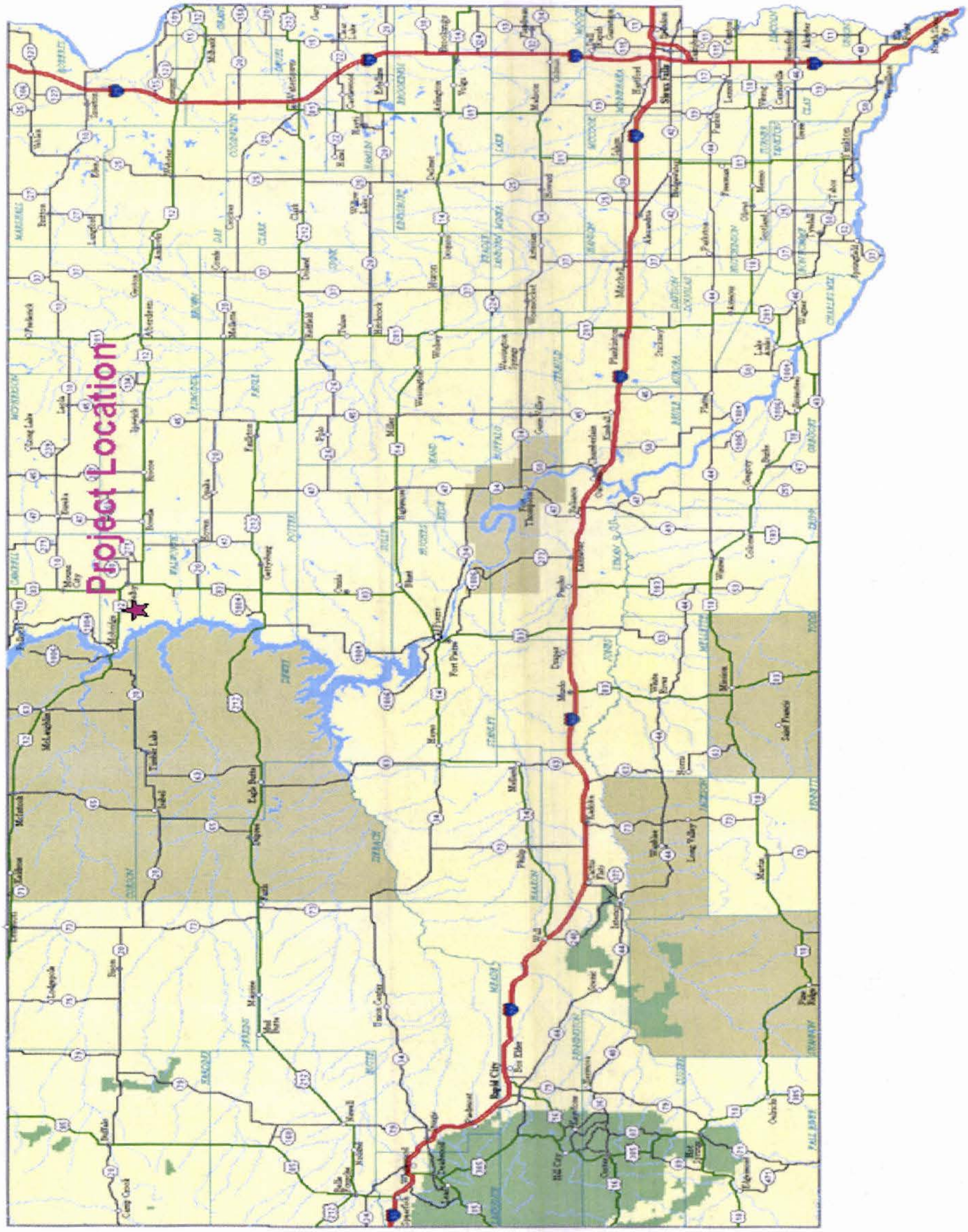


Figure 1. Site Location. (Adapted from South Dakota Office of Tourism, 2007).

reduction (SCR). No solid wastes are anticipated to be generated by the operation of the NO_x control system.

Particulates would be controlled through the use of filter fabric (baghouse) technology. The material collected in the baghouse system, generally referred to as fly ash, may be used as an additive to concrete or placed in a landfill for disposal. Sulfur dioxide control would be accomplished using a wet flue gas desulfurization (FGD) system. In this process, alkaline slurry (produced from mixing limestone and water) is sprayed into an absorber vessel to react with the SO_2 in the flue gas; calcium-sulfur compounds (primarily gypsum) are formed and then removed and dewatered for off-site sale or disposal. Mercury emissions would be controlled with carbon injection, a process that involves the direct injection of activated carbon into the flue gas stream. The spent carbon would be collected in the particulate control system, and may have a negative affect on the marketability of the fly ash for use as an admixture in concrete.

All of the waste streams resulting from the operation of air pollution control equipment, along with bottom ash (non combustible coal residue that settles to the bottom of the boiler) constitute the materials that may be required to be managed as solid waste at the proposed facility.

Solid Waste Composition and Quantity

Fly ash is composed of mainly amorphous spherical particles, ranging from about 10 to 100 μm in diameter, that are transported from the combustion area by exhaust gases and are collected by a particulate control system (US DOE, 2006). Major elements in fly ash typically include silicon, calcium, aluminum, sulfur, iron, magnesium, and sodium. Trace constituents may include zinc, vanadium and selenium. The results of recent analyses of a similar fly ash sample resulting from the combustion of PRB coal are shown in Appendix A. The analyses include a modified ASTM D3987 shake extraction test, performed with a 4:1 solution to solids ratio and "mineral analysis' of the ash. Fly ash represents approximately 80% of the ash produced at a typical PRB coal boiler; a 700 MW unit would produce approximately 160,000 tons of fly ash per year (Cris Miller, Basin Electric, personal communication). Rastogi and Charhut (2001) report a bulk density range of 43 to 76 pcf for PRB fly ash. For the purposes of this report, the bulk density of fly ash is estimated at 60 pcf.

Bottom ash consists of sand-size particles of amorphous silica and alumina that is taken from the bottom of the boiler furnace. The chemical analysis of bottom ash indicates it consists of oxides of silicon, aluminum, calcium, magnesium, and iron, with few other minor constituents. The results of a recent analysis of a similar bottom ash sample resulting from the combustion of PRB coal are shown in Appendix B. The analyses include a modified ASTM D3987 shake extraction test, performed with a 4:1 solution to solids ratio and "mineral analysis' of the ash. Bottom ash generation amounts are expected to be on the order of 20% of total ash or approximately 40,000 tons per year (Cris Miller, Basin Electric, personal communication). Das (2002) reports bottom ash bulk densities ranging from 72.6 to 104.4 pcf. The bulk density of bottom ash for this project is assumed to be similar to loose sand, at approximately 90 pcf.

FGD waste consists of silt size particles composed of calcium sulfite or calcium sulfate. No laboratory analysis of a similar FGD waste is currently available. The wet FGD wastes are proposed to be dried using vacuum filters to 80 to 90 percent solids content. Depending on how "hard" the flue gas is scrubbed, FGD waste is anticipated to be generated at a rate of approximately 50,000 tons per year. The density of the FGD waste is expected to be 60 pcf.

Based on an ash content of PRB coal of approximately 6%, the 700 MW plant would produce 160,000 tons of fly ash (198,000 cubic yards at a density of 60 pcf), 40,000 tons of bottom ash (33,000 cubic yards at a density of 90 pcf), and approximately 50,000 tons of FGD waste (62,000 cubic yards at a density of 60 pcf). The total volume of ash and FGD wastes potentially needing disposal amounts to approximately 293,000 cubic yards per year. Based on an estimated 50-year plant life, approximately 15 million cubic yards of materials may need to be managed at the proposed landfill.

Whenever possible, disposal of coal combustion wastes (CCWs) should be minimized by off-site utilization. For example, fly ash has been used as an admixture in concrete as a partial replacement for Portland cement and FGD material has been used in the manufacture of gypsum wall board (US DOE, 2006). Bottom ash has routinely been used as a replacement for sand to increase traction on roads during winter in North Dakota. Any CCWs that are not utilized off site would need to be disposed in an approved landfill.

SOUTH DAKOTA SOLID WASTE REGULATIONS

The statutes governing the storage and disposal of solid waste are found in South Dakota Codified Law (SDCL) 34A-6, and the rules developed to implement the statutes are found in Article 74:27 of the Administrative Rules of South Dakota (ARSD). The rules include seventeen chapters, detailing, among other things, the siting, design, operation, closure, and financial assurance requirements for landfills. Conformance with applicable state rules adds another layer of design constraints, in addition to the design constraints presented by the physical environment at the proposed project location. The Solid Waste Program of the South Dakota Department of

Environment and Natural Resources (DENR) is the government agency responsible for implementing the solid waste rules.

Regulatory Framework

As the proposed facility would receive more than 150,000 tons of solid waste each year, it is deemed a "Type I facility" by the SD solid waste rules. While there are no specific design requirements for Type I facilities, an additional "Phase I" permit application is required, along with increased public involvement and a longer (up to 270 days) permit application evaluation and processing period. The purpose of the Phase I application is to ensure the site is suitable for the development of the proposed facility. The bulk of the South Dakota solid waste rules apply to municipal solid waste landfills (MSWLFs) and there are no rules specific to the type of facility proposed herein; however, the rules have provisions and requirements for "other facilities." Based on a review of Article 74:27, it is assumed the "other facilities" criteria will be applied to the design and construction of the facility.

Site Selection Criteria

The facility would be subject to the location standards set forth in ARSD 74:27:11. The following location restrictions apply to the solid waste facility:

- Shall not cause significant adverse effect to wildlife, recreation, aesthetic value of an area, or state and federal threatened or endangered species.
- Shall not be located within a 100-yr floodplain.
- May not be located within 1,000 ft of an occupied dwelling, school, hospital, interstate or primary highway right-of-way.

- Shall not be closer than 1,000 ft of streams, creeks, lakes, reservoirs or other bodies of water classified for fish life.
- Shall not be located in unstable areas.
- Shall not be located in seismic impact zones or within 200 ft of a fault that has had displacement in Holocene time (this requirement applies specifically to MSWLFs, but should be included for this project to ensure long-term liner integrity).

Applicable Design and Monitoring Criteria

In general, a solid waste disposal facility must be designed, constructed, and operated to protect human health and prevent the degradation of the environment, including ambient groundwater quality, surface water quality, and air quality.

A surface water drainage and control system must be incorporated into the design to divert normal surface water flow and storm water run off around or away from areas where waste is present. The surface water drainage and control system must be designed to minimize the mixing of storm water with leachate and to handle the peak flow from a 25-year, 24-hour storm (ARSD 74:27:16:16). Typically, any water that comes in contact with waste is considered leachate and must be handled as such.

While there are specific liner requirements (composite liner, consisting of a compacted soil liner and a geomembrane) for MSWLFs in South Dakota, no prescriptive liner requirements apply to CCW landfills. The agency, however, may require liner systems for other disposal facilities when the wastes have a potential to pollute groundwater or surface water. In any case, the liner needs to be constructed of materials that have the strength, thickness, and chemical properties needed to prevent failure due to pressure gradients, contact with the waste or leachate, climatic conditions, stress of installation, and stress of daily operation (ARSD 74:27:12:17). The liner configuration is determined by the agency on a case-by-case basis. Based on the chemical analyses of the CCWs and the utility's experience with similar facilities in other states, it is anticipated that some type of liner system will be required. If a leachate collection system is used, it must be constructed of materials chemically resistant to the waste and leachate, be of sufficient strength to prevent collapse caused by the pressures of the overlying waste, be designed to prevent clogging throughout the active life and post closure care, and be designed to move leachate to a central collection point for treatment of disposal (ARSD 74:27:12:18). The final cover system for facilities other than MSWLF's must consist of a minimum of two feet of earthen material capable of maintaining perennial vegetation (ARSD 74:27:12:21). Facility-specific design details must be negotiated and ultimately approved by the DENR.

The agency may require a groundwater monitoring system for facilities other than MSWLFs. If required, the groundwater monitoring system must be located and designed to determine the ambient ground water quality and to detect the migration of leachate constituents from a facility. A sufficient number of wells must be located upgradient and downgradient of the waste disposal areas to ensure detection of contaminant migration. At least three wells must be located immediately downgradient of the waste disposal areas. Monitoring wells may be placed individually or in clusters (ARSD 74:27:19:03). The monitoring parameters and the monitoring frequencies required for a facility may be adjusted on a site-specific basis with prior approval by the agency. In no case may the monitoring frequency be less than once a year during the detection monitoring period (ARSD 74:27:19:07).

DESIGN CONSTRAINTS

The proposed landfill would be located west of the plant buildings on an approximately 300 acre parcel; the landfill footprint would cover approximately 200 acres. Figure 2 depicts the proposed plant layout and location of the landfill.

Climate

The site in north central South Dakota has a continental, sub-humid climate. Winters are typically cold and harsh, while summers are mild. The average monthly low temperatures vary from 2.0 F in January to 59 F in July. Average monthly high temperatures vary from 22.6 degrees F in January to 85.2 degrees F in July. The yearly average precipitation is 17.51 in. Most of the precipitation falls between April and September (High Plains Regional Climate Center, 2007).

Topography

Figure 3 depicts the general topography and drainage patterns at the site. An intermittent stream system crosses the site, and will need to be re-routed to allow for the development of the landfill. The intermittent stream in not a navigable water and is thus not subject to Corps of Engineers regulation. Further, the stream is not classified for fish life production by ARSD 74:51:03. Site drainage design will not be considered in this proposal.

Soils

Figure 4 depicts the general soil map for the study area. Soils present in the study areas include the Highmore series, consisting of very deep, well drained soils formed in silty glacial

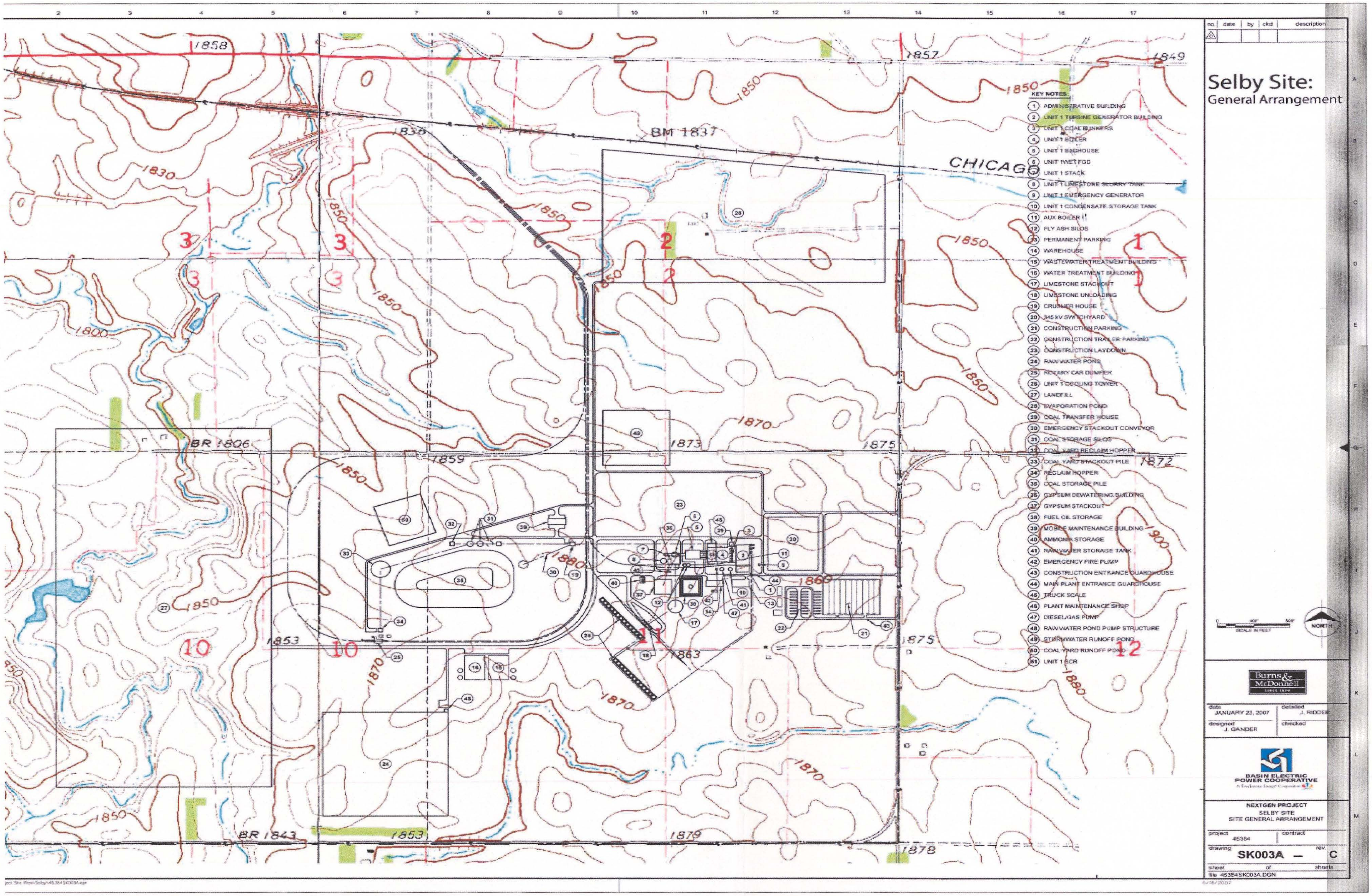


Figure 2. Proposed Plant Layout. (Basin Electric Power Cooperative).

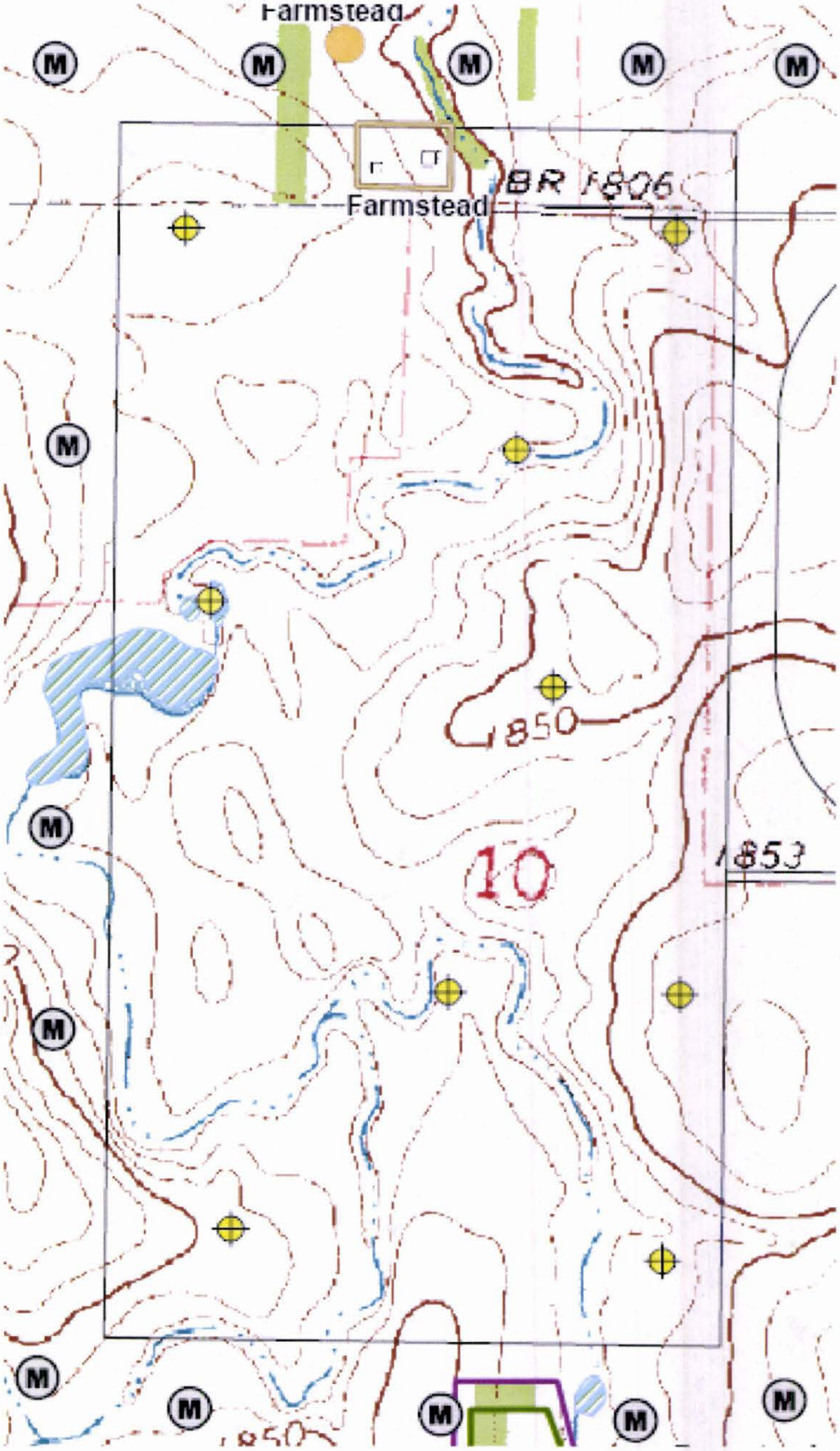
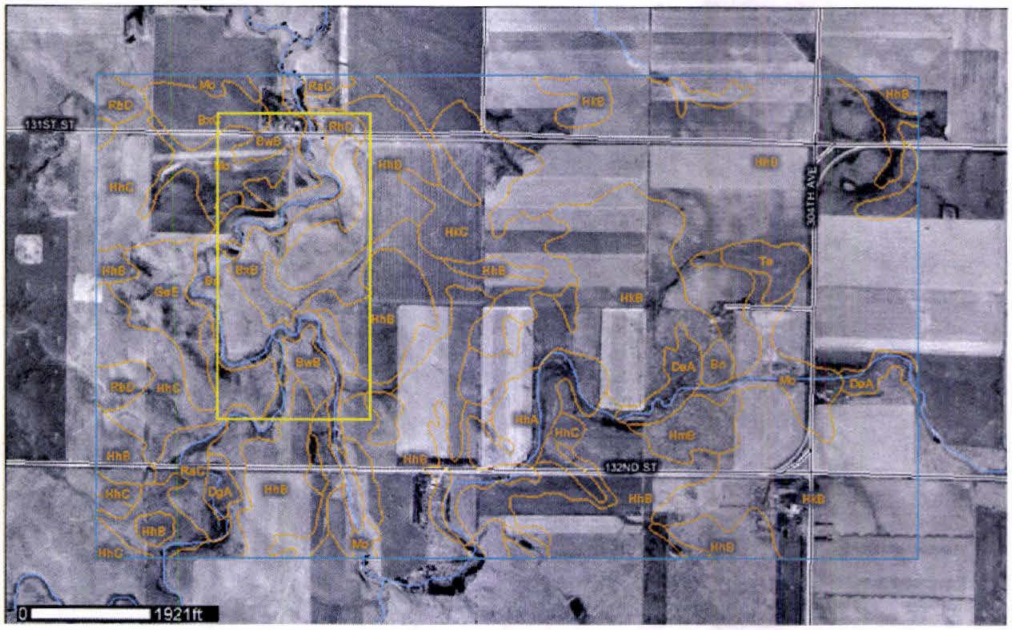


Figure 3. Topographic Map of Study Area. (Basin Electric Power Cooperative).

Soil Map



Map unit symbol	Map unit name	Rating	Acres in AOI	Percent of AOI
Tables — Surface Texture — Summary By Map Unit				
Summary by Map Unit — Walworth County, South Dakota				
Bn	Bon loam	loam	79.2	9.7%
BwB	Bowdle loam, 2 to 6 percent slopes	loam	38.5	4.7%
BxB	Bowdle-Wabek loams, 2 to 6 percent slopes	loam	20.9	2.6%
BxC	Bowdle-Wabek loams, 6 to 9 percent slopes	loam	18.9	2.3%
DgA	Demky-Jerauld complex, 0 to 2 percent slopes	loam	4.2	0.5%
Eg	Egas silty clay loam	silty clay loam	2.4	0.3%
GeE	Gettys clay loam, 9 to 40 percent slopes	clay loam	68.6	8.4%
HhA	Highmore silt loam, 0 to 2 percent slopes	silt loam	8.3	1.0%
HhB	Highmore silt loam, 2 to 6 percent slopes	silt loam	223.7	27.4%
HhC	Highmore silt loam, 6 to 9 percent slopes	silt loam	97.3	11.9%
HkB	Highmore-Eakin silt loams, 2 to 6 percent slopes	silt loam	10.8	1.3%
HkC	Highmore-Eakin silt loams, 6 to 9 percent slopes	silt loam	61.9	7.6%
Mo	Mobridge silt loam	silt loam	117.4	14.4%
RaC	Raber loam, 6 to 9 percent slopes	loam	15.7	1.9%
RbD	Raber-Gettys complex, 6 to 15 percent slopes	loam	45.5	5.6%
Te	Tetonka silt loam	silt loam	1.2	0.1%
W	Water		1.8	0.2%
Totals for Area of Interest (AOI)			**816.3**	**100.0%**

Figure 4. General Soil Map. (Adapted from Natural Resources Conservation Service, 2007).

drift on uplands, the Bowdle series, consisting of well drained soils formed in loamy alluvium underlain by sand and gravel on outwash plains and stream terraces, the Bon series, consisting of deep soils formed in alluvium on bottom lands of the glacial till plain, and the Mobridge series, consisting of deep, well and moderately well drained, moderately permeable soils formed in colluvial-alluvial sediments (National Resources Conservation Service, 2007). Geotechnical borings are planned to determine foundation conditions as well as to determine the suitability of in-situ soils for liner construction

Geology

The geologic map of Walworth County is depicted in Figure 5. The county is predominantly covered with glacial sediments of Pleistocene Age. Western portions of the county are covered by relatively recent loess deposits. The Cretaceous Pierre Shale is exposed in areas of western Walworth County adjacent to the Missouri River; these shale outcroppings are the only bedrock exposed in the county (Hedges, 1987).

The study area has been mapped as "older stagnation drift" which is believed to be of Late Wisconsinan Age. The till, referred to as "Till A," contains rock fragments of the Tongue River and Fox Hills Formations (Hedges, 1987), indicating the glacial ice may have come from the north-northwest. According to Hedges, 1987, the average thickness of the till in Walworth County is between 50 and 75 ft; the maximum thickness is 225 ft.

Based on a review of geologic cross sections near the site, it appears the Cretaceous Pierre shale would be the first bedrock unit encountered beneath the project location. A subsurface exploration program would provide additional detailed information regarding the geology and hydrogeology of the site. Lastly, a review of the United States Geological Survey (USGS) 2002 seismic map (Figure 6) shows the area lies in a region of relatively low seismic

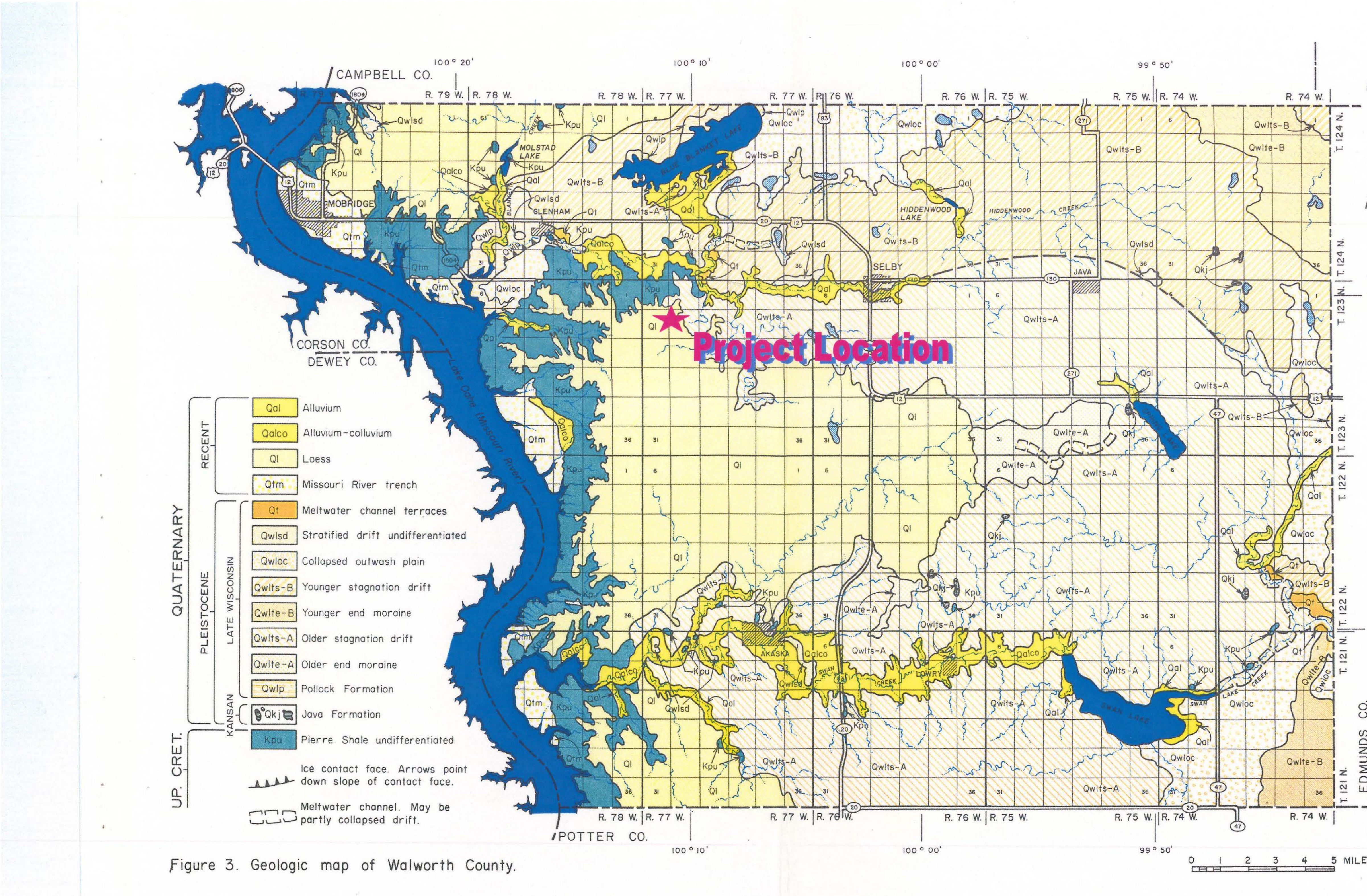


Figure 3. Geologic map of Walworth County.

Figure 5. Geologic Map of Walworth County. (Adapted from Hedges, 1987).

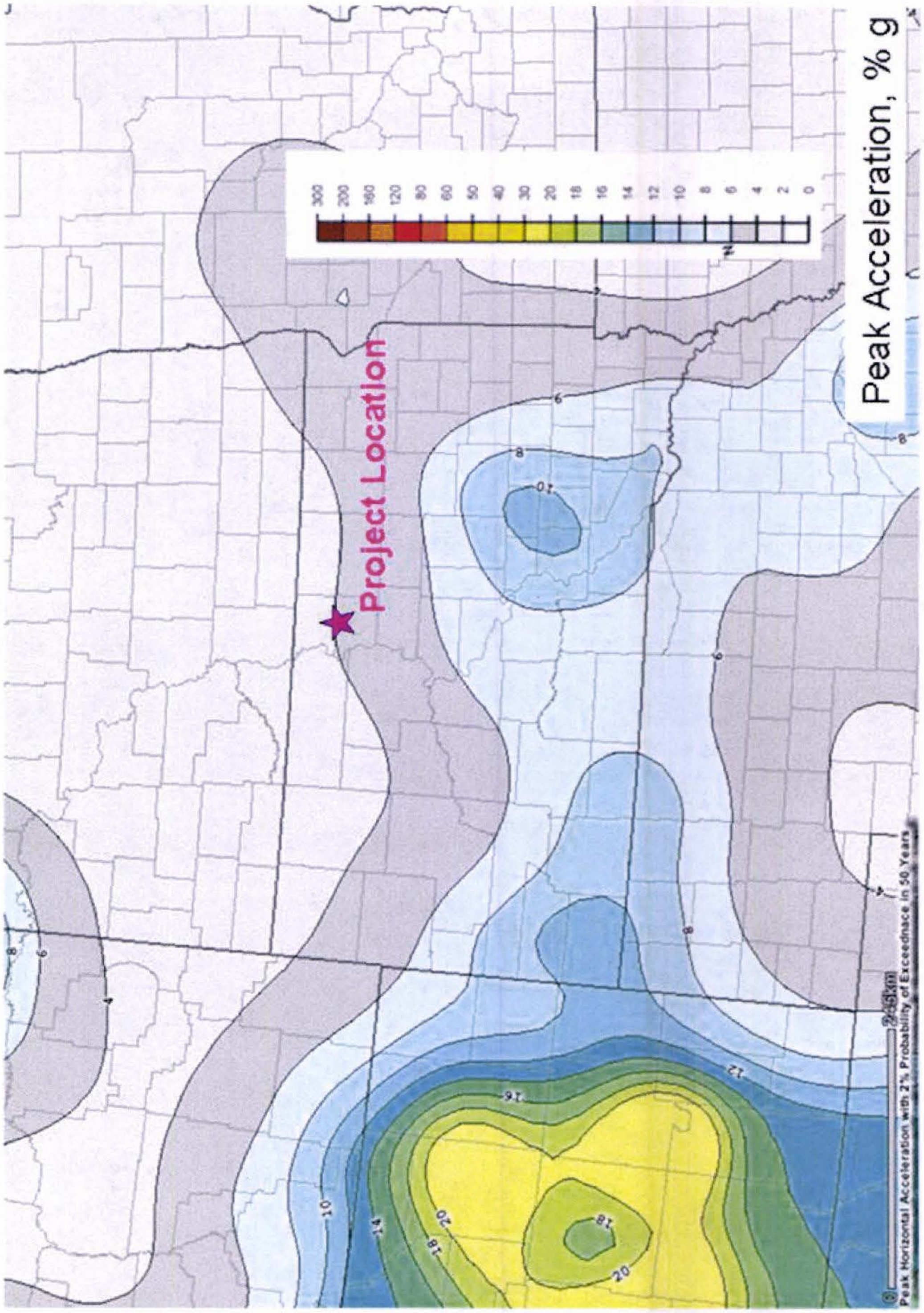


Figure 6. Regional Seismic Hazard Map. (Adapted from United States Geological Survey, 2002).

hazard, with a predicted maximum of four to six percent of the acceleration due to gravity (g) peak horizontal acceleration with a two percent probability of exceedance in 50 years. There are no Holocene faults mapped in the vicinity of the project location.

Regional Groundwater Resources

The nearest major glacial drift aquifer (see Figure 7) lies approximately one mile to the east of the proposed project location. The Grand Aquifer thickness averages 39 ft and is composed of glacial outwash sand and gravel that is generally overlain by a stony clay till (Kume, 1979). Dissolved solids in the Grand Aquifer range in concentration from 740 to 3,330 milligrams per liter, averaging 1,630 mg/l (Kume, 1979). Sandstones of the Dakota and Fall River Formations (dissolved solids concentration ranging from 1,800 to 6,090 mg/l) are major bedrock aquifers in the county and occur at depths of about 1,800 to 2,100 ft (Kume, 1979). For reference, the secondary drinking water standard for total dissolved solids is 500 mg/l (40 CFR Part 143). No significant groundwater resources appear to be present at the proposed site.

LANDFILL DESIGN

Over the 50 year life of the facility, an estimated 15 million cubic yards of "airspace" are needed to manage the wastes generated by plant operation. A number of considerations are necessary regarding the configuration of the facility, including ease of construction and operation, a logical progression of phased development and partial closure, and maximum thickness of waste placement (which affects the final height, slope, landfill area, and the consideration of foundation conditions). In addition, the effectiveness of landfill liner and cover

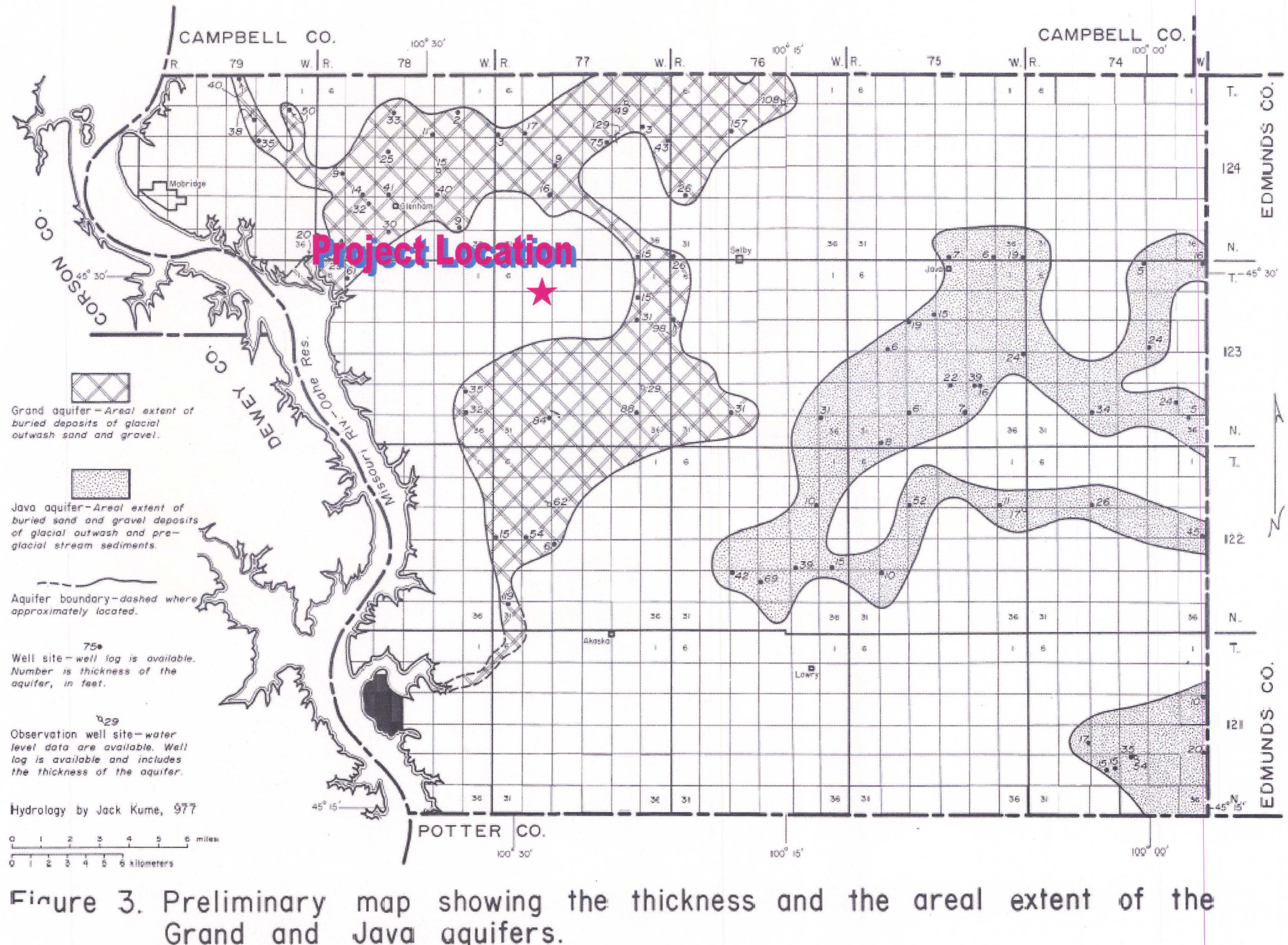


Figure 7. Glacial Aquifers in Walworth County. (Adapted from Kume, 1979).

systems must be analyzed to ensure leachate generation and migration are reduced to levels acceptable the regulatory agency.

Leachate Generation and Migration

Landfill leachate may be described as liquid that has percolated through layers of waste present in a landfill. Leachate may be composed of liquids that originate from a number of sources, including precipitation, groundwater, consolidation, initial moisture storage, and reactions associated with decomposition of waste materials. The chemical quality of leachate depends on a variety of factors, including the quantity of leachate produced, the chemical and physical composition of the buried wastes, and the chemical and biochemical reactions that may occur as the waste materials decompose. Most regulatory agencies appear to assume that any leachate produced will contaminate either ground or surface waters and thus require solid waste management facilities to incorporate engineered control measures such as liners and leachate collection systems.

The quantity of leachate produced in CCW landfills depends on the initial moisture content of the wastes and the amount of external water entering the landfill. Leachate production may be limited by placing relatively dry wastes into the landfill and by preventing, to the extent feasible, the entry of external water into the waste layers. To further reduce leachate migration, a leachate collection system may be added immediately above the bottom liner so that the bulk of the leachate that is produced is collected for subsequent treatment and disposal. As long as the integrity of the landfill structure and leachate control system is maintained, the migration of landfill leachate may be reduced to an extremely low volume.

HELP Model

The US Environmental Protection Agency (EPA) Hydrologic Evaluation of Landfill Performance (HELP) computer program is a hydrologic model of water movement across, into, through, and out of landfills (Schroeder et al., 1994). The program accepts weather, soil and design data and estimates changes in landfill water balance resulting from surface storage, snowmelt, runoff, infiltration, evapotranspiration, vegetative growth, soil moisture storage, lateral subsurface drainage, unsaturated vertical drainage, and leakage through soil, geomembrane or composite liners (Schroeder et al., 1994).

Landfill designs including various combinations of vegetation, cover soils, waste cells, lateral drain layers, low permeability barrier soils, and synthetic geomembrane liners may be modeled. The HELP model allows the rapid estimation of the amounts of runoff, evapotranspiration, drainage, leachate collection, and liner leakage that may be expected to result from the operation of a wide variety of landfill designs (Schroeder et al., 1994). As such, the model may be used in the comparison of design alternatives as judged by their water balances. The model may be used to evaluate open, partially closed, and fully closed sites. The model has been widely used by both landfill designers and regulators. A representative model output file from this design study is included in Appendix C.

Landfill Configuration

For a given amount of waste to be contained, the number of possible landfill configurations may be infinite. For a given height, a hemispherical shape offers the smallest landfill area and smallest final cover surface area for a given amount of waste. Construction of a hemispherical landfill, however, is not practical, mainly due to the steep slopes (greater than 45 percent or 1:1 on the lower half of the curved slope), among other considerations. A pyramidal shape is a practical alternative for landfill design, but the phasing of liner construction and waste placement, along with the application of partial final cover, may be difficult. Based on the proposed plant layout and the area available near the plant site for solid waste disposal, a landfill layout with a rectangular footprint of approximately 2200 ft by 4000 ft was chosen.

The goal of final cover system design is to limit the amount of precipitation that percolates into the underlying waste. Any liquid that passes through the cover system will contact the waste, and ultimately become leachate that requires collection and treatment. Another goal of the final cover system is to keep the waste isolated from the outside environment. The cover should be sloped to promote runoff (thus avoiding infiltration) but should not be susceptible to excessive erosion, thus exposing the waste.

Many cover systems include a compacted soil barrier layer (usually with a hydraulic conductivity specified as 1×10^{-7} cm/sec or less) to help reduce infiltration. Freeze-thaw effects and desiccation are known to increase the hydraulic conductivity of compacted soil barrier layers (Benson, 2000). Given the frost depth in north central South Dakota (estimated to be on the order of five ft), any compacted soil barrier layer in the cover system would likely be damaged by frost and/or desiccation, and would not function as designed. As such, the final cover system designs evaluated did not include a soil barrier layer, and instead, rely on the storage of infiltrated precipitation and subsequent evapotranspiration of the stored water. Such cover systems are oftentimes referred to as an evapotranspiration or "ET" cover systems. The final cover designs evaluated include 36 in. thick and 48 in. thick ET cover systems.

Determining an optimal final cover slope is a balance of competing factors. A landfill with a high final cover slope maximizes the use of the landfill footprint. Simply put, more waste may be placed on a smaller area, thus minimizing the cost per volume of waste disposed. Steeper slopes tend to increase runoff but also tend to increase erosion. A thicker fill may also pose problems with liner settlement or deformation that result from limitations in the strength of the liner material and/or site foundation conditions. A thicker fill would likely result in a higher final elevation for the landfill, thus causing a concomitant increase in the visual impact on adjacent land.

South Dakota has no specific design criteria relating to landfill slope. In neighboring North Dakota, landfill slopes above 15 percent require a detailed demonstration to show that excessive erosion will not occur. For this design analysis, landfill slopes of 5, 10, and 15 percent and final cover thicknesses of 36 and 48 in. were evaluated using the HELP model. Table 1 illustrates the subtle relationships between cover thickness, slope, ET, runoff, and infiltration.

Table 1. Landfill Cover System HELP Model Results.

Cover Thickness (in.)	Slope (percent)	E.T. (percent)	Runoff (percent)	Infiltration (percent)
36	5	95.51	1.61	2.78
36	10	95.49	1.66	2.79
36	15	94.06	3.51	2.36
48	5	96.80	1.45	1.70
48	10	96.80	1.46	1.69
48	15	95.23	3.32	1.40

The results depict the yearly average value of each output parameter for a 50 year simulation, reported in percent of HELP model predicted annual average precipitation (16.89 in. in Selby, South Dakota).

Cover System

For any given slope, the 48 in. thick cover system exhibits better performance (as measured by infiltration) than the 36 in. cover. At a 10 percent slope, the 48 in. cover allows 1.69 percent infiltration while the 36 in. cover allows 2.79 percent infiltration, a difference of 1.12 percent. Given an average annual precipitation of 16.89 in., 1.12 percent difference amounts to 0.189 in. of additional infiltration. This difference is likely due to the additional storage capacity and greater evaporative zone depth of the 48 in. cover.

As depicted in Table 1, there is little difference in the overall performance between 5 and 10 percent cover systems. For a given thickness, the 5 and 10 percent cover systems exhibit only minute differences in output parameters. Only when slope is increased from 10 to 15 percent do we observe measurable differences in runoff, evapotranspiration, and infiltration. In general, when slope is increased, the increase in runoff is offset (roughly balanced) by a decrease in evapotranspiration.

Foundation Conditions

Given the 2200 ft by 4000 ft rectangular landfill footprint and 5, 10, or 15 percent slopes, maximum waste thicknesses are calculated to be 55, 110, or 165 ft. Considering the relative percentage of the waste types and waste unit weights, a fill thickness of 55 ft results in a maximum vertical stress of 3490 lb/ft^2, while fill thicknesses of 110 and 165 ft, result in maximum vertical stresses of 6980 and 10,460 lb/ft^2, respectively.

Ultimate soil bearing capacity was estimated to be 14,500 lb/ft^2 using Terzaghi's equation for ultimate bearing capacity (as presented in Das, 2002). Bearing capacity assumptions and calculations are presented in Appendix D. Based on the estimated ultimate soil bearing capacity, a 55 ft thick fill results in a factor of safety (FS) of 4.16, a 110 ft fill results in a FS of 2.08, and a 165 ft thick fill results in a FS of 1.38. In general, a FS greater than 1.00 indicates there will be no failure of the evaluated component or system; however, given the uncertainty in measurement methods and variation of soil parameters in the field, a FS of 2.00 or greater is desirable. Soil bearing capacity will be reevaluated once site specific information becomes available.

Recommended Landfill Configuration

Because of the apparent design constraint due to foundation conditions, a design for a landfill with a footprint of 2200 ft by 4000 ft (about 202 acres) and a final cover slope of 10 percent (see Figure 8) will be evaluated in detail. Ten percent slopes also offer a good compromise between the competing factors of runoff and erosion. If a leachate collection system is used, the bottom liner must be sloped to facilitate the flow of liquids to a network of perforated leachate collection pipe. The "waffle pattern" depicted in Figure 9 allows for 2 percent bottom liner slopes and limits the maximum leachate flow distance along the bottom liner to a collection pipe to approximately 350 ft.

The facility will be constructed in eight distinct 25.25-acre phases as shown in Figure 8. Orderly, sequential construction allows areas of new bottom liner to be constructed while other areas of the landfill (that have been filled to final grade) are closed. Further, it is important to cover any newly constructed liner with waste or other insulating material to protect it from freeze-thaw damage. Phased construction limits the area of newly constructed liner requiring frost protection to a manageable size and reduces the amount of non-contact water that must be managed as leachate.

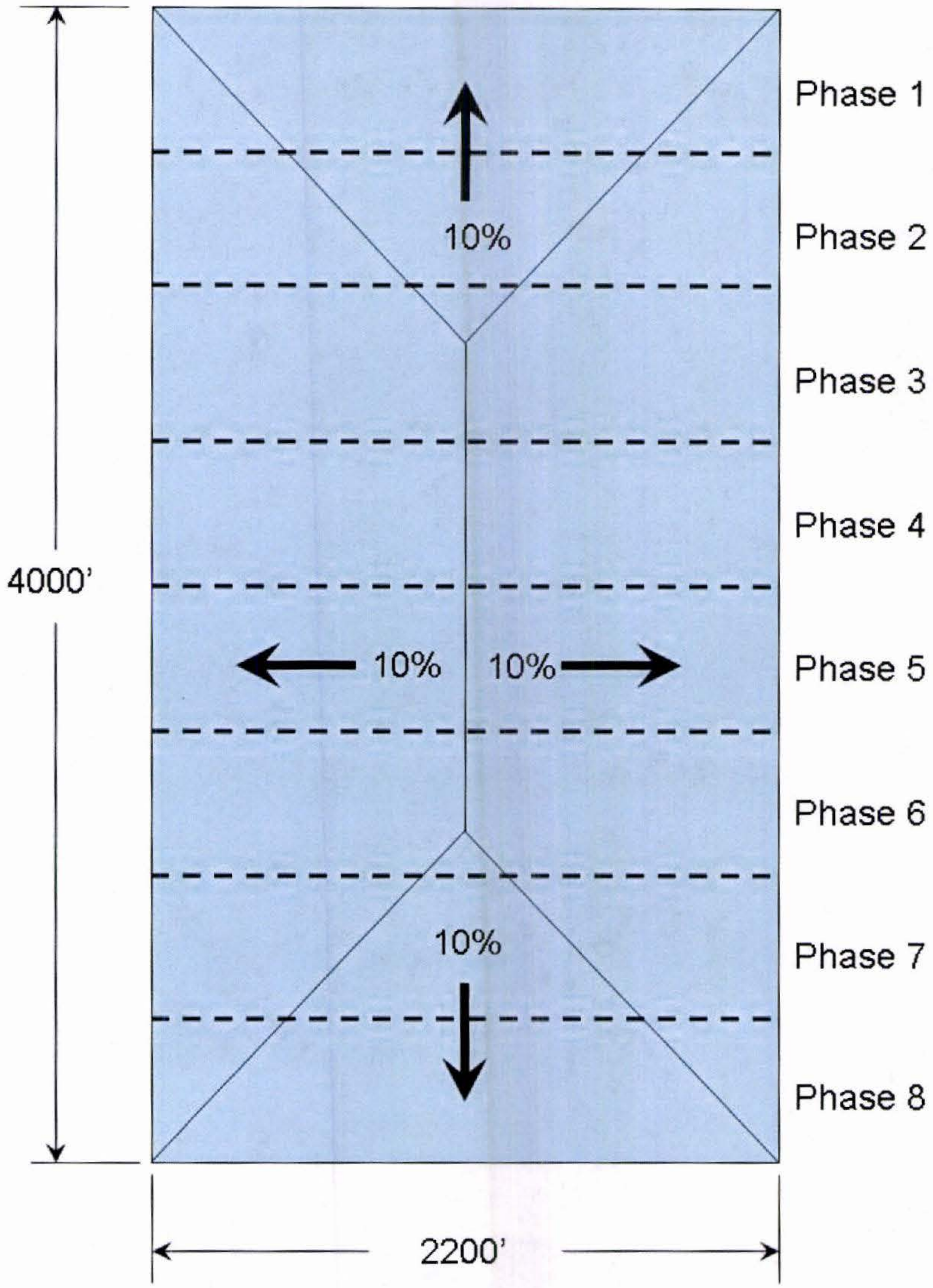


Figure 8. Landfill Footprint and Phasing.

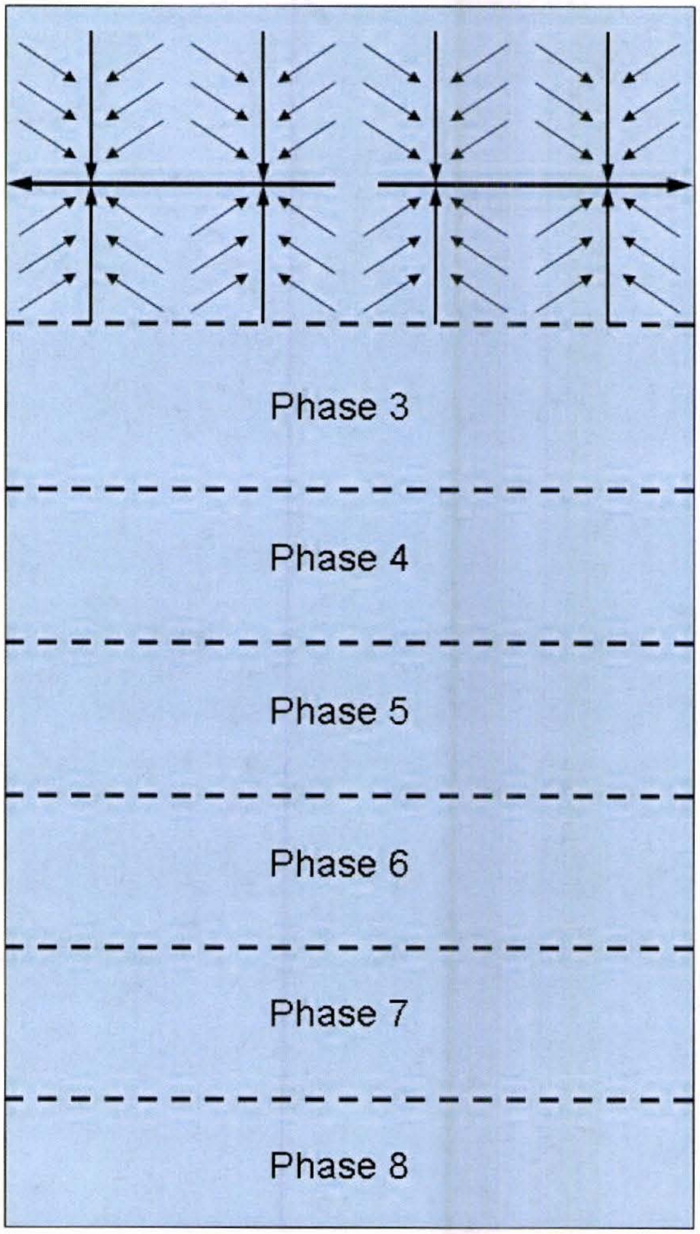


Figure 9. Leachate Collection System "Waffle Pattern" Detail.

Open Landfill HELP Model Results

The landfill was modeled in open conditions for a variety of liner and leachate collection system (LCS) configurations. Modeling parameters for all simulations included 24 ft of waste (HELP model default soil texture number 30, (fly ash)). The evaporative zone depth was set as 10 in., which is consistent with HELP model user's guide recommendations for bare soil and no vegetation. Climatic data was uniform for all model iterations, and was based on default HELP model data (Bismarck, North Dakota) that were adjusted for factors such as precipitation, latitude, temperature, etc., based on site specific meteorological data for Selby, South Dakota. Because the landfill will be built in distinct phases, with portions under closure as new areas of liner are being constructed, the HELP model simulation was limited to five years. Results are shown in Table 2.

Table 2. Open Landfill HELP Model Results.

Liner	LCS	E.T. (percent)	Runoff (percent)	LCS (percent)	Percolation (percent)
24 in. CCL	No	86.3	11.6	0	1.34
48 in. CCL	No	86.3	11.6	0	1.34
24 in. CCL	Yes	86.3	11.6	0.00012	1.12
48 in. CCL	Yes	86.3	11.6	0.00012	1.12
24 in. composite	No	86.3	11.6	0	0.0056
24 in. composite	Yes	86.3	11.6	0.399	0.0034

For all simulations, model results show evapotranspiration and runoff to be the dominant factors in the yearly water balance, accounting for approximately 86.4 percent and 11.6 percent, respectively. Added together, they account for 98 percent of the annual water balance.

Adding a leachate collection system (12 in. thick granular drainage layer with $K=1x10^{-3}$ cm/s, bottom liner slope of 2 percent and a maximum of 350 ft leachate flow distance) did very little to increase the performance of the CCL systems. While infiltration was reduced from 0.228 to 0.202 in. (1.3 to 1.2 percent), the 0.1 percent reduction is due to an increase in water storage in the waste, LCS, and CCL. Just a small fraction of a percent (0.00012 percent) is captured by the LCS. This result is probably due to the extremely low volume of liquid that actually reaches the CCL; the liquid likely infiltrates the liner before it has a chance to flow to the LCS perforated pipe drainage system.

Open conditions were also modeled with a composite liner, which consists of a compacted soil liner overlain by a flexible membrane liner (FML). Specifically, the composite liner consists of 24 in. CCL ($K=1 \times 10^{-7}$ cm/s) overlain by a 60 mil high density polyethylene (HDPE) geomembrane. Realistic values, based on the HELP Model User's Guide (Schroeder et al., 1994), were assumed for FML material and installation quality (one pinhole per acre, four installation defects per acre, and good, not excellent, FML placement quality). Again, evapotranspiration and runoff were dominant in the water balance for the design. Without a LCS, infiltration was reduced to 0.00095 in., or about 0.006 percent; however, there was in increase in the liquid that went into storage (0.346 in. or about 2 percent) and an increase in the average head on the bottom liner. With the addition of a LCS, infiltration was reduced even further, to 0.00059 in. LCS drainage increased to 0.0679 in., or about 0.4 percent.

Based on the six open landfill simulations, annual leachate flux through the liner system ranged from about 0.00059 to 0.2276 in. A large gain in performance resulted from the addition of the FML. In all cases, however, the total volume of average annual infiltration through the liner system was relatively low, ranging from 826 ft^3/acre down to 2.14 ft^3/acre/year.

Closed Landfill HELP Model Results

Twelve closed landfill configurations were evaluated with the HELP model to assess the effects of varying cover thickness and liner/LCS designs. Layer and climate data were kept consistent with earlier simulations except waste layer thickness was increased to 36 ft and the modeling period was increased to 50 years, to simulate steady state conditions.

As previously noted and depicted in Table 3, evapotranspiration is the dominant factor in the water balance. For the 36 in. thick cover system, evapotranspiration accounted for the average annual removal of 16.1 in. of liquid (approximately 95.5 percent). Increasing the cover thickness to 48 in. resulted in removal of 16.4 in. of liquid, or about 96.8 percent. Runoff is slightly higher for the 36 in. cover (0.267 in. versus 0.233 for the 48 in. cover). Evapotranspiration plus runoff amounted to 16.4 in. (97.1 percent) for the 36 in. cover and 16.6 in. (98.2 percent) for the 48 in. cover.

Table 3. Closed Landfill HELP Model Results

Cover Thickness	Liner	LCS	E.T. (percent)	Runoff (percent)	LCS (percent)	Liner Flux (percent)
36 in.	24 in. CCL	No	95.6	1.58	0	2.36
36 in.	48 in. CCL	No	95.6	1.58	0	2.36
36 in.	24 in. CCL	Yes	95.6	1.58	0.00023	2.32
36 in.	48 in. CCL	Yes	95.6	1.58	0.00023	2.32
36 in.	24 in. composite	No	95.6	1.58	0	0.106
36 in.	24 in. composite	Yes	95.6	1.58	2.11	0.016
48 in.	24 in. CCL	No	96.8	1.39	0	1.53
48 in.	48 in. CCL	No	96.8	1.39	0	1.53
48 in.	24 in. CCL	Yes	96.8	1.39	0.00015	1.50
48 in.	48 in. CCL	Yes	96.8	1.39	0.00014	1.50
48 in.	24 in. composite	No	96.8	1.39	0	0.072
48 in.	24 in. composite	Yes	96.8	1.39	1.39484	0.011

Similar to the open conditions landfill simulation, little difference was noted in CCL performance based on liner thickness or the presence or absence of a LCS. Again, the addition of a LCS provides little improvement, handling 0.00002 to 0.00004 in. or about 0.0726 to 0.145 ft^3/acre/year. When a composite liner is utilized, however, the LCS flow increases to 0.356 in. or about 1290 ft^3/acre/year. Thus, it seems reasonable to conclude that an LCS provides almost no benefit and is thus unnecessary when using a CCL system; however, the usefulness of a LCS is clear and should be included when utilizing a composite liner system.

Cost Estimates

Estimating the cost of various design options is fairly straightforward; one simply adds the costs of a particular combination of design components. Project cost estimates are based on observations made during a16-year tenure at the North Dakota Health Department. The cost of soil for the landfill cover system is estimated to be \$2.75/yd^3. The cost of CCL is slightly higher, estimated at \$3.25/yd^3, due to the additional compaction requirements necessary to achieve the hydraulic conductivity design specification of 1 $\times 10^{-7}$ cm/s or less. HDPE FML is estimated at \$0.01 per mil thickness/ft^2. Table 4 depicts the per acre cost for the various design components and Table 5 illustrates the performance differences for probable landfill designs.

Table 4. Design Component Cost Estimate.

Design Component	Approximate Cost per Acre
36 in. Cover System	\$13,310
48 in. Cover System	\$17,747
30 mil HDPE	\$13,068
60 mil HDPE	\$26,136
24 in. CCL (K = 1 X 10^{-7} cm/s or less)	\$10,486
LCS (12 in. granular drainage layer)	\$0 (use bottom ash generated by plant)

Table 5. Design Performance and Cost.

Cover system thickness	Liner System	Annual Liner Flux (ft^3/acre)	Cost (Acre)
36 in.	24 in. CCL	1446.	$23,796
48 in.	24 in. CCL	937	$28,232
36 in.	24 in. composite	9.66	$49,932
48 in.	24 in. composite	6.53	$54,378

Given the relatively minor increase in cost for a 48 in. thick versus a 36 in. thick cover system, a 48 in. cover is preferred due to its better performance when using a CCL. When using a composite liner, however, the overall improvement resulting from the use a 48 in. thick cover system is negligible; only about 3.12 ft^3 less leachate passes through each acre of the liner per year. Accordingly, the additional expense of installing a 48 in. thick cover with a composite bottom liner system is probably not warranted.

Based on estimated costs of materials and installation, a landfill with a 48 in. thick cover system coupled with a 24 in. thick CCL would cost approximately $28,232 per acre while a facility with a 36 in. thick cover system coupled with a 24 in. composite liner would cost approximately $49,935 per acre. The reduction in overall infiltration of approximately 938 ft^3/acre/year costs an additional $21,703, or about $23.33/ ft^3. A facility with a composite liner, however, would be constructed with a LCS that requires pumping and other maintenance indefinitely.

Leachate Management

When using a CCL, no leachate is collected for designs constructed with or without a LCS. Any liquid that infiltrates the cover ultimately becomes leachate and permeates the bottom liner. When using a 36 in. thick cover system and a composite liner, however, approximately

1290 ft^3 of leachate would be collected per acre each year. If the leachate was not routinely removed, the waste layers would become completely saturated over time, creating the so-called "bath tub effect." For a 200 acre closed facility, approximately 258,000 ft^3 (about 5.9 acre feet) of leachate would need to be pumped from the facility and evaporated, treated or otherwise disposed per year. Operation of the leachate collection system would be necessary in perpetuity. Managing a closed facility indefinitely results in undefined costs; this presents an untenable situation for most entities.

Considering the originally proposed designs, the preferred alternative would be a landfill with a 48 in. cover system and a 24 in. CCL. This option, however, results in the infiltration of approximately 937 ft^3 of leachate per acre per year through the bottom liner, or about 2.57 ft^3/acre/day. Based on waste analyses presented in Appendix A, leachate concentrations are expected to be on the order of 3000-5000 ppm total dissolved solids. Depending on the characteristics of the local groundwater (yet to be determined), the addition of the leachate may have negligible effect on groundwater quality. Contaminant transport modeling may indicate impacts to groundwater would be minimal; regardless, regulatory agency acceptance of the preferred design alternative may be difficult. As such, an additional design alternative is discussed below.

Alternative Design Recommendation

While not originally included in the design proposal, a landfill configuration with a synthetic layer in the cover system deserves some analysis. By greatly reducing infiltration through the cover system, very little leachate will be generated and thus leachate management becomes less an issue. The FMLs used in landfill cover systems are generally thinner than those used in bottom liner systems (30 mil versus 60 mil) since they are not required to resist the heavy loading of the overlying waste. The cost of the FML used in a cover system is approximately half the cost of one used in a liner system.

The design incorporating a FML in the cover system results in performance that is significantly improved over the non-FML design configurations. Evapotranspiration (98.4 percent) and runoff (1.40 percent) account for a large majority (99.8 percent) of the annual water balance. Only 0.137 percent infiltrates though the bottom liner, which amounts to 83.7 ft^3/acre/year, or about 0.223 ft^3/acre/day (1.71 gallons/acre/day). Estimated cost for this design is $41,300 per acre. There is no LCS and thus leachate management/treatment is not required. Table 6 includes the alternative design and depicts the performance and cost of each option.

Table 6. Alternative Design Performance and Cost.

Cover system thickness	Liner System	Annual Liner Flux (ft^3/acre)	Cost (Acre)
36 in.	24 in. CCL	1446.5	$23,796
48 in.	24 in. CCL	937.4	$28,232
36 in.	24 in. composite	9.656	$49,932
48 in.	24 in. composite	6.534	$54,378
48 in. with 30 mil FML	24 in. CCL	83.7	$41,301

The recommended design includes a 48 in. thick ET cover system incorporating a 30 mil FML and a 24 in. CCL bottom liner at a total estimated cost of $41,301 per acre. A 48 in. thick cover system maximizes the storage and subsequent evapotranspiration of incident precipitation. When the soil layer is underlain by a 30 mil FML to further limit infiltration, the production of leachate is significantly reduced. Since no LCS is used with the CCL, perpetual leachate management in not a concern. The cost is $13,069 per acre more than the previously preferred design consisting only of soil components; annual liner flux, however, is reduced by about 91 percent. Total costs for the 202 acre facility with 15,000,000 yd^3 of disposal capacity are estimated to be $8,343,000, or about $0.56 per yd^3 of airspace.

GROUNDWATER MONITORING SYSTEM

General

South Dakota regulations for groundwater monitoring at solid waste facilities are specifically applicable to municipal solid waste (MSW) landfills. The DENR, however, may require other facilities to comply with applicable provisions of ARSD 74:27:10 (Groundwater Monitoring). Given facility size and waste characteristics, it is anticipated that groundwater monitoring will need to be addressed in the permitting of the proposed facility.

The purpose of a groundwater monitoring system is to determine background or ambient ground water quality and to detect the migration of leachate constituents from a facility. As such, wells must be located upgradient and downgradient of the disposal area, with a statutory requirement for a minimum of three downgradient wells. ARSD 74:27:10 also indicates that the monitoring system must meet the requirements of 40 CFR Part 258 (also commonly referred to as "Subtitle D"), the federal regulation for MSW landfills. Since the proposed facility is not an MSW landfill, it is anticipated that the agency will take a hybrid approach in its view of groundwater monitoring. In particular, the groundwater parameter list for Subtitle D includes more than 60 organic compounds that are not present in CCWs and thus are not relevant for facility monitoring.

Well Spacing

A key feature of Subtitle D is the "relevant point of compliance", which is a down-gradient monitoring well where samples are taken to determine if a statistically significant increase over background water quality has occurred. According to Subtitle D, the relevant point of compliance shall be no more than 150 meters from the disposal area, and must be located on land owned by the facility operator (40 CFR Part 258).

Spreadsheet calculations incorporating a variety of groundwater gradients and aquifer hydraulic conductivities were completed to estimate groundwater flow velocities and hence travel times to downgradient wells. As depicted in Table 7, unless a contaminant source is located in an aquifer with a relatively high hydraulic conductivity (say greater than 1×10^{-4} cm/s), or in an area with a high hydraulic gradient, it is unlikely (given estimated travel time) that a contaminant would reach a downgradient monitoring well 150 m from a landfill during the life of the facility, including the postclosure monitoring period (typically 30 years). These simple calculations, however, do not account for important factors such as dispersion and retardation, which would result in a reduction in contaminant concentration at distance, or groundwater flow in fractures, which would result in a decrease in contaminant travel times. A potential remedy to the issue described above is to move the downgradient wells much closer to the landfill boundary (for instance 25 m). Depending on the gradient and aquifer hydraulic conductivity, however, even a 25 m distance is no guarantee that contaminants will reach a downgradient well during the life of the facility.

Table 7. Travel Time to Downgradient Well.

			travel time to	travel time to	travel time to
K (cm/s)	dv/dh	n	150 m well (years)	75 m well (years)	25 m well (years)
1.00E-06	0.1	0.3	1,430	713	238
1.00E-06	0.01	0.3	14,300	7,130	2,380
1.00E-06	0.001	0.3	143,000	71,300	23,800
1.00E-05	0.1	0.3	143	71.3	23.8
1.00E-05	0.01	0.3	1,430	713	238
1.00E-05	0.001	0.3	14,300	7,130	2,380
1.00E-04	0.1	0.3	14.3	7.13	2.38
1.00E-04	0.01	0.3	143	71.3	23.8
1.00E-04	0.001	0.3	1,430	713	238
1.00E-03	0.1	0.3	1.43	0.713	0.238
1.00E-03	0.01	0.3	14.3	7.13	2.38
1.00E-03	0.001	0.3	143	71.3	23.8

As a contaminant moves through an aquifer, it is diluted by mixing with noncontaminated water, a process known as dispersion. Dispersion occurs along the groundwater flow path (longitudinal dispersion) and normal to it (lateral dispersion). Longitudinal dispersivity appears to be related to scale; the larger the area of measurement, the larger the value of dispersivity (Gelhar, et al., 1992). Transverse or horizontal dispersivity is also related to scale, with values on the order of one-tenth of longitudinal dispersivity (Gelhar, et al., 1992). The difference in longitudinal and transverse dispersivities gives rise to the elongated tear-drop shape of contaminant plumes. Moving monitoring wells closer to the landfill boundary may provide for early detection, however, this may also result in lateral gaps between the wells that allow narrow plumes to move undetected.

To address this issue, USEPA software (Optimal Well Locator or "OWL" version 1.2) was used to visualize hypothetical plume characteristics in a number of aquifer flow settings.

OWL is a user-friendly program that uses typically available site data and simple algorithms to predict contaminant plume size and shape as a function of groundwater gradient, aquifer hydraulic conductivity, contaminant concentration, and time, among other variables.

OWL is a simple model and is not intended to replace comprehensive groundwater flow and contaminant transport and fate models (Srinivasan, et al., 2004). The aquifer is assumed to be homogeneous and isotropic, with constant thickness. The contaminant source is assumed to provide a constant stream of dissolved contaminant from a vertical plane through the thickness of the aquifer. Plume concentrations predicted by OWL (see Appendix E) are based on the Domenico solution (Domenico, 1987) which has been adapted for two-dimensional transport (Srinivasan, et al., 2004).

OWL Modeling Results

Figures 10 through 12 provide graphical representations of hypothetical plumes from a leachate release near the midpoint of the landfill. In all cases, groundwater flow is from north to south, with a gradient of approximately 0.005. Effective porosity was assumed to be 0.25, and longitudinal and transverse dispersivities were assumed to be 10 meters and 1 meter, respectively. Modeling will be updated using site specific information when it becomes available.

The source concentration was assumed to be 3000 mg/l, which should give conservative results, since no parameter has a leachate concentration greater than 1000 mg/l. Accordingly, the model results should show "worse than worst case" contaminant transport results. The OWL simulations were conducted at hydraulic conductivities of 3.15 meters per year (about 1×10^{-5} cm/sec), 31.5 meters per year (about 1×10^{-4} cm/sec), and 315 meters per year (about 1×10^{-3} cm/sec) to provide some insight into a range of hydrogeologic settings.

The color-coded contour intervals depicted in the OWL contaminant plume simulations are on a logarithmic scale; the two highest intervals are yellow, indicating a concentration increase of 10 to100 mg/l, and red, indicating an increase of 100 to1000 mg/l. If ambient groundwater concentrations are on the order of 1600 mg/l, it is likely that an increase of 10-100 mg/l in a downgradient monitoring well would be attributed to temporal variations in groundwater quality, and not a release. An increase of 1000 mg/l, however, would undoubtedly be viewed as a significant increase. As such, only areas of the OWL plumes shown in red are

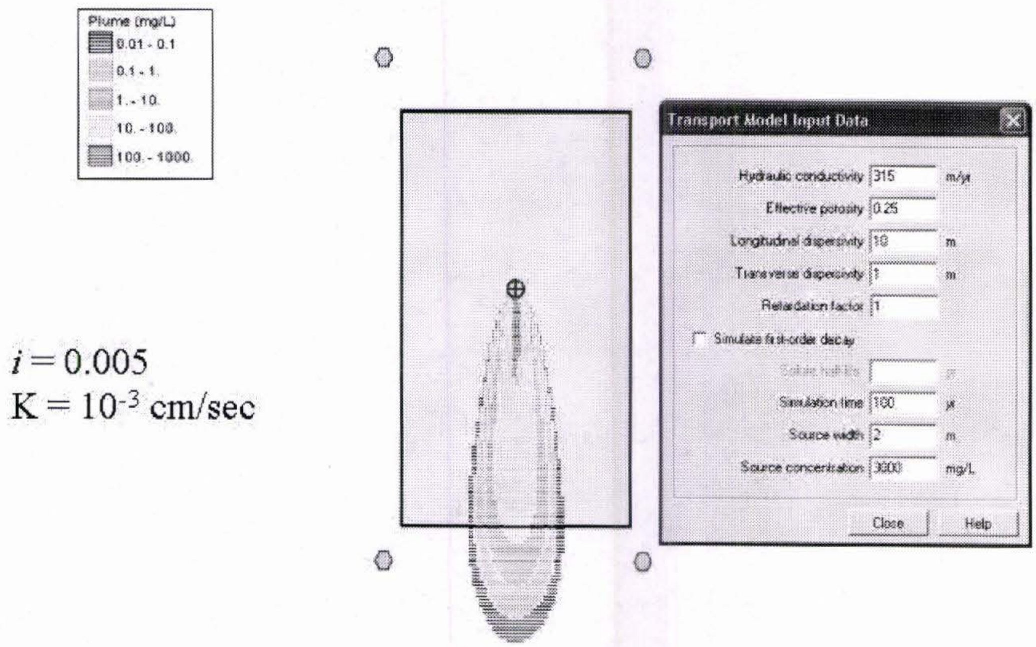


Figure 10. OWL Plume, K = 315 meters per year.

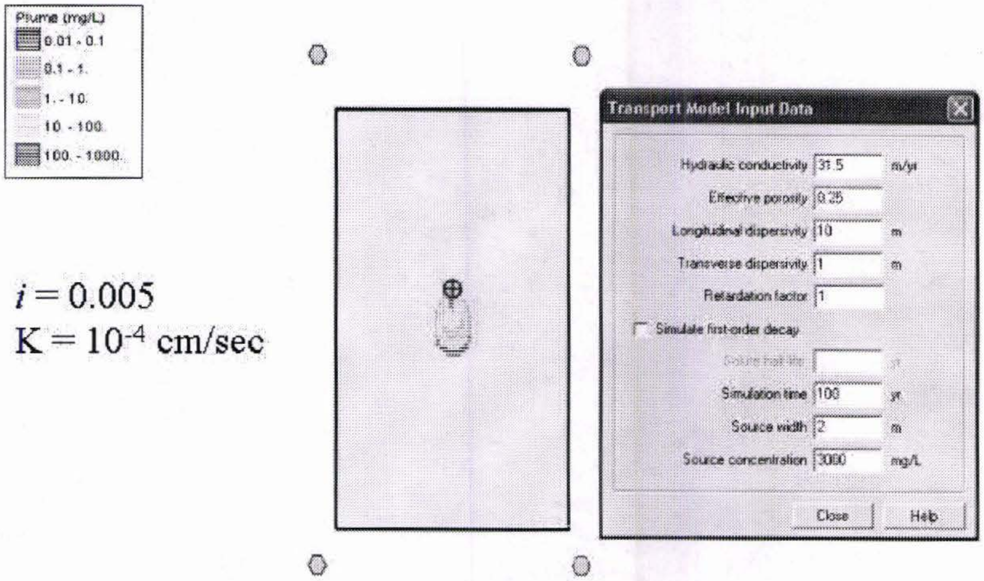


Figure 11. OWL Plume, K = 31.5 meters per year.

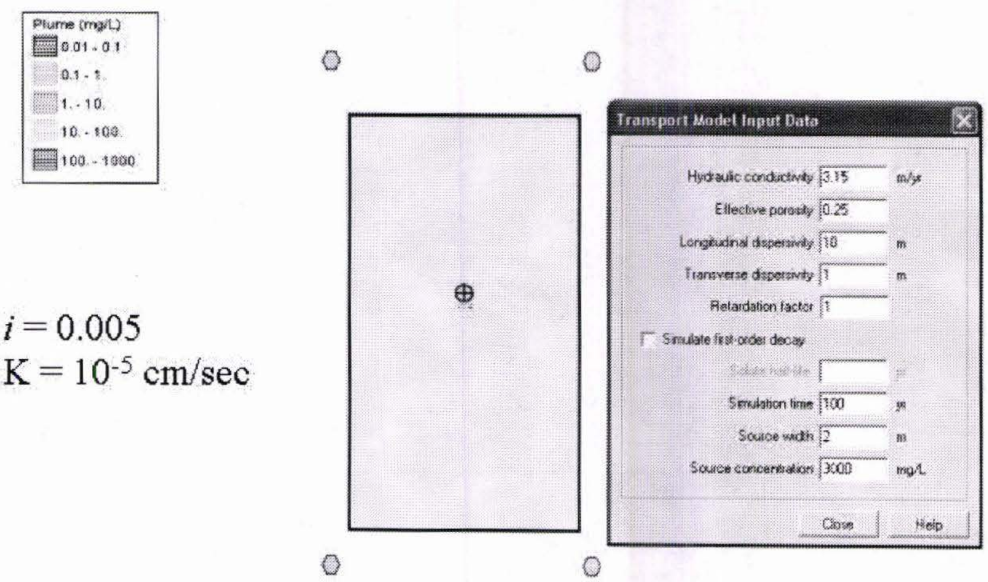


Figure 12. OWL Plume, K = 3.15 meters per year.

likely to be detected through a site monitoring program. The yellow, green, blue and violet areas of the plume, while exhibiting an increase, would not likely be deemed a statistically significant increase or cause for concern.

Given an analysis of groundwater transport times and an analysis of dispersion with the OWL model, it is apparent that only a contaminant source near the downgradient boundary of the landfill would be detected. If other areas within the landfill boundary were to leak, they would not be detected within the life of the facility and postclosure care period. Plume widths depicted by the OWL model are on the order of 10 to 20 m; the downgradient landfill boundary width is approximately 700 m. As a result, between 35 and 70 downgradient wells would be needed to provide complete coverage. Given the characteristics of the waste and the relatively low probability of severe impacts, however, this number could likely be reduced; many agencies default to a 100 m lateral spacing between downgradient wells.

Based on the hypothetical landfill layout and groundwater flow regime depicted in this design study, the recommended monitoring network consists of the followings: two upgradient monitoring wells; two side-gradient monitoring wells along the east and west sides of the landfill (total of four wells); and, 10 downgradient wells with a lateral spacing of approximately 70 meters located a maximum of 25 m from the landfill boundary. The 202 acre site would be monitored by a total of 16 wells.

Parameter list

Based on a review of the waste leaching test data (Appendices A and B), a suite of six "indicator" parameters (calcium, sodium, boron, sulfate, bicarbonate and chloride) are recommended for the groundwater monitoring program. Many monitoring plans (including the groundwater monitoring provisions of Subtitle D) place emphasis on trace metals; however, the extremely low concentrations (less than 1 milligram per liter) of theses parameters in leachate would make them essentially undetectable. Instead, the proposed monitoring parameters are present in concentrations up to several hundred milligrams per liter.

Up- and downgradient wells would be sampled and analyzed semiannually for the life of the facility and the anticipated 30 year postclosure care period. After background water quality has been established (typically eight sampling events), the monitoring results would be analyzed using Shewert Cumulative Sum (CUSUM) Control Charts to determine if a statistically significant increase of any of the indicator parameters has occurred in a downgradient well.

CONCLUSIONS

Solid wastes generated through the operation of the boiler and associated plant air pollution control systems would be disposed at an onsite 202-acre landfill with 10 percent slopes. The proposed facility would manage approximately 685 tons of waste each day; a design capacity of 15,000,000 yd^3 is required for the anticipated 50-year life of the landfill.

The recommended design includes a 48 in. thick ET cover system incorporating a 30 mil FML and a 24 in. CCL bottom liner; estimated costs are $41,301 per acre. The cover system maximizes the storage and evapotranspiration of precipitation and limits infiltration. Since no LCS is used with the CCL, perpetual leachate management in not a concern. The cost is $13,069 per acre more than a design consisting only of soil components; annual liner flux, however, is reduced by about 91 percent. Total cost for the 15,000,000 yd^3 disposal facility is estimated to be $8,343,000, or about $0.56 per yd^3 of airspace.

No site specific hydrogeologic information is available; important characteristics such as hydraulic conductivity and hydraulic gradient are not known. Calculations using a range of aquifer parameters and the gradients were completed to provide an envelope of contaminant travel time values. US EPA Optimal Well Locator (OWL) program was used to account for the effects of dispersion in determining the lateral spacing of wells. Based on the calculations and modeling discussed above, the site would be monitored by 10 downgradient wells located a maximum of 25 m from the landfill boundary with a lateral spacing of approximately 70 meters. Two upgradient and four side gradient wells would provide additional information on aquifer gradient and background water quality. Based on waste leaching test results, six "indicator" parameters (calcium, sodium, boron, sulfate, bicarbonate and chloride) are recommended for the groundwater monitoring program. Monitoring wells would be sampled and analyzed semiannually; results would be analyzed using Shewert Cumulative Sum (CUSUM) Control Charts to determine if a statistically significant increase of any of the indicator parameters has occurred in a downgradient well

APPENDICES

APPENDIX A

Fly Ash Chemical Analysis

MINNESOTA VALLEY TESTING LABORATORIES, INC.

1126 N. Front St. ~ New Ulm, MN 56073 ~ 800-782-3557 ~ Fax 507-359-2890
1411 S. 12th St. ~ Bismarck, ND 58502 ~ 800-279-6885 ~ Fax 701-258-9724
35 W. Lincoln Way ~ Nevada, IA 50201 ~ 800-362-0855 ~ Fax 515-382-3885
www.mvtl.com

MEMBER ACIL

Jim Berg
Basin Electric Power Cooperative
1717 E. Interstate Avenue
Bismarck ND 58503

Report Date: 27 Apr 07
Lab Number: 07-M617
Work Order #:81-425
Account #: 002040
Date Sampled:
Date Received: 5 Apr 07 16:00
PO #: 492162

Sample Description: Unit 1 Fly Ash
Sample Site: Laramie River Station

	As Received Result		Method RL	Method Reference	Date Analyzed	Analyst
pH	12.0	units	N/A	SM4500 H+ B	10 Apr 07 15:38	Rick
Specific Conductance	3445	umhos/cm	N/A	SM2510-B	10 Apr 07 15:38	Rick
Total Alkalinity	780	mg/l CaCO3	4	SM2320-B	10 Apr 07 15:38	Rick
Phenolphthalein Alk	738	mg/l CaCO3	4	SM2320-B	10 Apr 07 15:38	Rick
Bicarbonate	< 4	mg/l CaCO3	4	SM2320-B	10 Apr 07 15:38	Rick
Carbonate	84	mg/l CaCO3	4	SM2320-B	10 Apr 07 15:38	Rick
Hydroxide	696	mg/l CaCO3	0	SM2320-B	10 Apr 07 15:38	Rick
Tot Dis Solids(Summation)	859	mg/l	NA	SM1030-F	17 Apr 07 9:37	Calculated
Total Hardness as CaCO3	449	mg/l	NA	SM2340-B	13 Apr 07 14:54	Calculated
Hardness in grains/gallon	26.3	gr/gal	NA	SM2340-B	13 Apr 07 14:54	Calculated
Cation Summation	17.1	meq/L	NA	SM1030-F	13 Apr 07 14:54	Calculated
Anion Summation	16.0	meq/L	NA	SM1030-F	17 Apr 07 9:37	Calculated
Percent Error	3.46	%	NA	SM1030-F	17 Apr 07 9:37	Calculated
Sodium Adsorption Ratio	3.60		NA	USDA 20b	13 Apr 07 14:54	Calculated
Radium 226	< 1	pCi/l	1		23 Apr 07 13:59	
Total Organic Carbon	< 0.5	mg/l	0.5	SM5310-C	13 Apr 07 8:00	Jesse
Fluoride	3.14	mg/l	0.10	SM4500-F-C	10 Apr 07 15:38	Rick
Sulfate	14.0	mg/l	5.00	EPA 375.4	17 Apr 07 9:37	Rick
Chloride	2.9	mg/l	1.0	SM4500-Cl-E	13 Apr 07 10:05	Morgan
Nitrate-Nitrite as N	0.22	mg/l	0.10	EPA 353.2	12 Apr 07 10:00	Morgan
Ammonia-Nitrogen as N	0.55	mg/l	0.10	EPA 350.1	12 Apr 07 14:15	Morgan
Phosphorus as P - Total	< 0.1	mg/l	0.10	EPA 365.1	11 Apr 07 14:30	Morgan
Mercury - Total	0.0003	mg/l	0.0002	EPA 245.1	13 Apr 07 9:00	Eric
Chemical Oxygen Demand	< 1	mg/l	1.0	HACH 8000	10 Apr 07 11:00	Jesse
Calcium - Total	180	mg/l	0.5	6010	13 Apr 07 14:54	Stacy
Magnesium - Total	< 0.5	mg/l	0.5	6010	13 Apr 07 14:54	Stacy
Sodium - Total	176	mg/l	0.5	6010	13 Apr 07 14:54	Stacy
Potassium - Total	18.2	mg/l	0.5	6010	13 Apr 07 14:54	Stacy
Aluminum - Total	5.69	mg/l	0.10	6010	13 Apr 07 8:46	Stacy
Barium - Total	7.62	mg/l	0.10	6010	13 Apr 07 8:46	Stacy
Beryllium - Total	< 0.01	mg/l	0.01	6010	13 Apr 07 8:46	Stacy
Cadmium - Total	< 0.01	mg/l	0.01	6010	13 Apr 07 8:46	Stacy
Chromium - Total	< 0.05	mg/l	0.05	6010	13 Apr 07 8:46	Stacy
Cobalt - Total	< 0.1	mg/l	0.10	6010	13 Apr 07 8:46	Stacy
Copper - Total	< 0.05	mg/l	0.05	6010	13 Apr 07 8:46	Stacy
Iron - Total	< 0.1	mg/l	0.10	6010	13 Apr 07 8:46	Stacy
Manganese - Total	< 0.05	mg/l	0.05	6010	13 Apr 07 8:46	Stacy
Molybdenum - Total	< 0.1	mg/l	0.10	6010	13 Apr 07 8:46	Stacy

RL = Method Reporting Limit

Elevated "Less Than Result" (<): @ = Due to sample matrix
! = Due to sample quantity
= Due to sample concentration
+ = Due to extract volume

CERTIFICATION: MN LAB # 038-999-267 ND # ND-00016

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www.mvtl.com

MEMBER ACIL

Report Date: 27 Apr 07
Lab Number: 07-M617
Work Order #:81-425
Account #: 002040
Date Sampled:
Date Received: 5 Apr 07 16:00
PO #: 492162

Jim Berg
Basin Electric Power Cooperative
1717 E. Interstate Avenue
Bismarck ND 58503

Sample Description: Unit 1 Fly Ash
Sample Site: Laramie River Station

	As Received Result		Method RL	Method Reference	Date Analyzed	Analyst
Zinc - Total	0.14	mg/l	0.05	6010	13 Apr 07 8:46	Stacy
Boron - Total	0.38	mg/l	0.10	6010	11 Apr 07 9:54	Stacy
Antimony - Total	< 0.002	mg/l	0.0020	6020	16 Apr 07 16:42	Claudette
Arsenic - Total	< 0.002	mg/l	0.0020	6020	16 Apr 07 16:42	Claudette
Lead - Total	< 0.002	mg/l	0.0020	6020	16 Apr 07 16:42	Claudette
Selenium - Total	0.0051	mg/l	0.0020	6020	17 Apr 07 9:25	Claudette
Silver - Total	< 0.01**	mg/l	0.0010	6020	16 Apr 07 16:42	Claudette
Thallium - Total	< 0.002	mg/l	0.0020	6020	16 Apr 07 16:42	Claudette
Vanadium - Total	0.0053	mg/l	0.0020	6020	16 Apr 07 16:42	Claudette
Uranium	< 0.002	mg/l	0.002	6020	16 Apr 07 16:42	Claudette
pH (Shake Extraction)	11.6	units	0.10	ASTM D3987	10 Apr 07 10:30	Shannon
% Solids (Shake Ext.)	99.8		0.10		10 Apr 07 10:30	Shannon

1 analyses were performed on the extract from ASTM Method 3987 with a modified solution to
lids ratio of 4:1.
** Silver was reported at ICP Reporting Limits for historical purposes.

Approved by: C Cantep

RL = Method Reporting Limit

Elevated "Less Than Result" (<): @ = Due to sample matrix
! = Due to sample quantity
= Due to sample concentration
+ = Due to extract volume

CERTIFICATION: MN LAB # 038-999-267 ND # ND-00016

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35 W. Lincoln Way ~ Nevada, IA 50201 ~ 800-362-0855 ~ Fax 515-382-3885
www.mvtl.com
MEMBER ACIL

Sample Number: 07-M614

Report Date: 4/23/07

Jim Berg
Basin Electric Power Cooperative
1717 E. Interstate Avenue
Bismarck ND 58503

Work Order #: 81-424
P.O. #: 492162

Date Received: 4/ 5/07

Sample Description: Unit 1 Fly Ash
Sample Site: Laramie River Station

MINERAL ANALYSIS OF ASH

Aluminum Oxide in Ash	15.54	wt. %
Barium Oxide in Ash	0.62	wt. %
Calcium Oxide in Ash	26.05	wt. %
Iron Oxide in Ash	5.79	wt. %
Magnesium Oxide in Ash	5.68	wt. %
Manganese Dioxide in Ash	0.03	wt. %
P2O5 in Ash	0.80	wt. %
Potassium Oxide in Ash	0.32	wt. %
Silicon Dioxide in Ash	35.23	wt. %
Sodium Oxide in Ash	2.09	wt. %
Strontium Oxide in Ash	0.41	wt. %
SO3 in Ash	1.58	wt. %
Titanium Dioxide in Ash	1.19	wt. %

Approved By: D. Zander

APPENDIX B

Bottom Ash Chemical Analysis

MINNESOTA VALLEY TESTING LABORATORIES, INC.
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35 W. Lincoln Way ~ Nevada, IA 50201 ~ 800-362-0855 ~ Fax 515-382-3885
www.mvtl.com

MEMBER ACIL

Report Date: 26 Sep 05
Lab Number: 05-M1554
Work Order #:81-762
Account #: 002040
Date Sampled:
Date Received: 1 Sep 05 14:40
PO #: 492162

Jim Berg
Basin Electric Power Cooperative
1717 E. Interstate Avenue
Bismarck ND 58503

Sample Description: Unit #3 Bottom Ash
Sample Site: Laramie River Station

	As Received Result		Method RL	Method Reference	Date Analyzed	Analyst
pH	11.1	units	N/A	SM4500 H+ B	2 Sep 05 16:45	Deb
Specific Conductance	2231	umhos/cm	N/A	SM2510-B	2 Sep 05 16:45	Deb
Total Alkalinity	348	mg/l CaCO3	4	SM2320-B	6 Sep 05 14:15	Deb
Phenolphthalein Alk	258	mg/l CaCO3	4	SM2320-B	6 Sep 05 14:15	Deb
Bicarbonate	< 4	mg/l CaCO3	4	SM2320-B	6 Sep 05 14:15	Deb
Carbonate	180	mg/l CaCO3	4	SM2320-B	6 Sep 05 14:15	Deb
Hydroxide	168	mg/l CaCO3	0	SM2320-B	6 Sep 05 14:15	Deb
Total Dissolved Solids	1350	mg/l	NA	EPA 160.1	7 Sep 05 15:00	Calculated
Total Hardness as CaCO3	132	mg/l	NA	SM2340B	7 Sep 05 13:24	Calculated
Hardness in grains/gallon	7.71	gr/gal	NA	N/A	7 Sep 05 13:24	Calculated
Cation Summation	20.4		NA	N/A	8 Sep 05 10:01	Calculated
Anion Summation	22.0		NA	N/A	7 Sep 05 15:00	Calculated
Percent Error	-3.84	%	NA	N/A	8 Sep 05 10:01	Calculated
Sodium Adsorption Ratio	14.6		NA	N/A	7 Sep 05 13:24	Calculated
Radium 226	3.2 +/- 0.6pCi/l				9 Sep 05 14:30	
Uranium	< 0.002	mg/l	0.0020		22 Sep 05 9:34	Claudette
Total Organic Carbon	3.8	mg/l	0.5	SM5310-C	9 Sep 05 8:00	Wayne
Fluoride	< 0.1	mg/l	0.10	SM4500-F-C	6 Sep 05 14:15	Deb
Sulfate	530	mg/l	5.00	EPA 375.4	7 Sep 05 12:30	Brandon
Chloride	138	mg/l	1.0	SM4500-Cl-E	7 Sep 05 15:00	Brandon
Nitrate-Nitrite as N	1.42	mg/l	0.10	SM 4500-NO3F	2 Sep 05 16:00	Brandon
Ammonia-Nitrogen as N	0.15	mg/l	0.10	SM4500-NH3-H	2 Sep 05 14:30	Brandon
Phosphorus as P - Total	0.15	mg/l	0.10	SM4500-P-F	6 Sep 05 14:15	Brandon
Mercury - Total	< 0.0002	mg/l	0.0002	EPA 245.1	12 Sep 05 8:30	Eric
Chemical Oxygen Demand	13.9	mg/l	1.0	HACH 8000	12 Sep 05 8:30	Wayne
Calcium - Total	52.8	mg/l	0.5	6010	7 Sep 05 13:24	Stacy
Magnesium - Total	< 0.5	mg/l	0.5	6010	7 Sep 05 13:24	Stacy
Sodium - Total	388	mg/l	0.5	6010	7 Sep 05 13:24	Stacy
Potassium - Total	33.0	mg/l	0.5	6010	7 Sep 05 13:24	Stacy
Aluminum - Total	76.6	mg/l	0.10	6010	8 Sep 05 10:01	Stacy
Barium - Total	0.36	mg/l	0.10	6010	8 Sep 05 10:01	Stacy
Beryllium - Total	< 0.01	mg/l	0.01	6010	8 Sep 05 10:01	Stacy
Cadmium - Total	< 0.01	mg/l	0.01	6010	8 Sep 05 10:01	Stacy
Chromium - Total	0.20	mg/l	0.05	6010	8 Sep 05 10:01	Stacy
Cobalt - Total	< 0.1	mg/l	0.10	6010	8 Sep 05 10:01	Stacy
Copper - Total	< 0.05	mg/l	0.05	6010	8 Sep 05 10:01	Stacy
Iron - Total	< 0.1	mg/l	0.10	6010	8 Sep 05 10:01	Stacy
Manganese - Total	< 0.05	mg/l	0.05	6010	8 Sep 05 10:01	Stacy

RL = Method Reporting Limit

Elevated "Less Than Result" (<): @ = Due to sample matrix
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CERTIFICATION: MN LAB # 038-999-267 ND # ND-00016

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www.mvtl.com
MEMBER ACIL

Report Date: 26 Sep 05
Lab Number: 05-M1554
Work Order #:81-762
Account #: 002040
Date Sampled:
Date Received: 1 Sep 05 14:40
PO #: 492162

Jim Berg
Basin Electric Power Cooperative
1717 E. Interstate Avenue
Bismarck ND 58503

Sample Description: Unit #3 Bottom Ash
Sample Site: Laramie River Station

	As Received Result		Method RL	Method Reference	Date Analyzed	Analyst
Molybdenum - Total	0.22	mg/l	0.10	6010	8 Sep 05 10:01	Stacy
Zinc - Total	0.13	mg/l	0.05	6010	8 Sep 05 10:01	Stacy
Boron - Total	0.17	mg/l	0.10	6010	9 Sep 05 9:56	Stacy
Antimony - Total	< 0.002	mg/l	0.0020	6020	7 Sep 05 10:40	Claudette
Arsenic - Total	0.0049	mg/l	0.0020	6020	7 Sep 05 10:40	Claudette
Lead - Total	< 0.002	mg/l	0.0020	6020	7 Sep 05 10:40	Claudette
Selenium - Total	0.0133	mg/l	0.0020	6020	7 Sep 05 10:40	Claudette
Silver - Total	< 0.01**	mg/l	0.00020	6020	7 Sep 05 10:40	Claudette
Thallium - Total	< 0.002	mg/l	0.0020	6020	7 Sep 05 10:40	Claudette
Vanadium - Total	0.0456	mg/l	0.0020	6020	7 Sep 05 10:40	Claudette
pH (Shake Extraction)	11.2	units	0.10	ASTM D3987	2 Sep 05 9:15	Claudette
% Solids (Shake Ext.)	98.2		0.10		1 Sep 05 16:00	Claudette

All analyses were performed on the extract from ASTM Method D3987; modified with a solution to solid ratio of 4:1.

** Silver was reported at ICP Reporting Limits for historical purposes.

Approved by: C. Cantrell

RL = Method Reporting Limit

Elevated "Less Than Result" (<): # = Due to sample matrix
! = Due to sample quantity
\# = Due to sample concentration
\+ = Due to extract volume

CERTIFICATION: MN LAB # 027-999-267 ND # ND-00016

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www.mvtl.com

MEMBER ACIL

Sample Number: 05-M1555

Report Date: 9/14/05

Jim Berg
Basin Electric Power Cooperative
1717 E. Interstate Avenue
Bismarck ND 58503

Work Order #: 81-763
P.O. #: 492162

Date Received: 9/ 1/05

Sample Description: Unit #3 Bottom Ash
Sample Site: Laramie River Station

MINERAL ANALYSIS OF ASH

Aluminum Oxide in Ash	8.13	wt. %
Barium Oxide in Ash	0.56	wt. %
Calcium Oxide in Ash	24.36	wt. %
Iron Oxide in Ash	6.99	wt. %
Magnesium Oxide in Ash	6.30	wt. %
Manganese Dioxide Ash	0.05	wt. %
Phosphorus Pentoxide	0.57	wt. %
Potassium Oxide in Ash	0.56	wt. %
Silicon Dioxide in Ash	47.90	wt. %
Sodium Oxide in Ash	1.99	wt. %
Strontium Oxide in Ash	0.42	wt. %
SO3 in Ash	0.90	wt. %
Titanium Dioxide in Ash	1.49	wt. %

Approved By: D. Zander

APPENDIX C

Typical HELP Model Output

```
******************************************************************************
******************************************************************************
 **
**
 **
**
 **              HYDROLOGIC EVALUATION OF LANDFILL PERFORMANCE
**
 **                HELP MODEL VERSION 3.07  (1 NOVEMBER 1997)
**
 **                  DEVELOPED BY ENVIRONMENTAL LABORATORY
**
 **                    USAE WATERWAYS EXPERIMENT STATION
**
 **              FOR USEPA RISK REDUCTION ENGINEERING LABORATORY
**
 **
**
 **
**
******************************************************************************
******************************************************************************


 PRECIPITATION DATA FILE:     C:\DOCUME~1\K\DESKTOP\HELPMO~1\USER\SELP.D4
 TEMPERATURE DATA FILE:       C:\DOCUME~1\K\DESKTOP\HELPMO~1\USER\SELT.D7
 SOLAR RADIATION DATA FILE:   C:\DOCUME~1\K\DESKTOP\HELPMO~1\USER\SELRAD.D13
 EVAPOTRANSPIRATION DATA:     C:\DOCUME~1\K\DESKTOP\HELPMO~1\USER\SEL48EV.D11
 SOIL AND DESIGN DATA FILE:   C:\DOCUME~1\K\DESKTOP\HELPMO~1\USER\4CL1.D10
 OUTPUT DATA FILE:            C:\DOCUME~1\K\DESKTOP\HELPMO~1\USER\4CL1.OUT


 TIME:  14: 7     DATE:   2/28/2008


******************************************************************************

      TITLE:  48 inch cap, 24 inch CCL, no LCS

******************************************************************************


      NOTE:  INITIAL MOISTURE CONTENT OF THE LAYERS AND SNOW WATER WERE
               COMPUTED AS NEARLY STEADY-STATE VALUES BY THE PROGRAM.
```

LAYER 1

TYPE 1 - VERTICAL PERCOLATION LAYER
MATERIAL TEXTURE NUMBER 10

```
THICKNESS                    =     48.00   INCHES
POROSITY                     =      0.3980 VOL/VOL
FIELD CAPACITY               =      0.2440 VOL/VOL
WILTING POINT                =      0.1360 VOL/VOL
INITIAL SOIL WATER CONTENT   =      0.1454 VOL/VOL
EFFECTIVE SAT. HYD. COND.    =  0.119999997000E-03 CM/SEC
NOTE:  SATURATED HYDRAULIC CONDUCTIVITY IS MULTIPLIED BY  4.63
       FOR ROOT CHANNELS IN TOP HALF OF EVAPORATIVE ZONE.
```

LAYER 2

TYPE 1 - VERTICAL PERCOLATION LAYER
MATERIAL TEXTURE NUMBER 30

```
THICKNESS                    =    360.00   INCHES
POROSITY                     =      0.5410 VOL/VOL
FIELD CAPACITY               =      0.1870 VOL/VOL
WILTING POINT                =      0.0470 VOL/VOL
INITIAL SOIL WATER CONTENT   =      0.1870 VOL/VOL
EFFECTIVE SAT. HYD. COND.    =  0.499999987000E-04 CM/SEC
```

LAYER 3

TYPE 3 - BARRIER SOIL LINER
MATERIAL TEXTURE NUMBER 16

```
THICKNESS                    =     24.00   INCHES
POROSITY                     =      0.4270 VOL/VOL
FIELD CAPACITY               =      0.4180 VOL/VOL
WILTING POINT                =      0.3670 VOL/VOL
INITIAL SOIL WATER CONTENT   =      0.4270 VOL/VOL
EFFECTIVE SAT. HYD. COND.    =  0.100000001000E-06 CM/SEC
```

GENERAL DESIGN AND EVAPORATIVE ZONE DATA

NOTE: SCS RUNOFF CURVE NUMBER WAS COMPUTED FROM DEFAULT SOIL DATA BASE USING SOIL TEXTURE #10 WITH AN EXCELLENT STAND OF GRASS, A SURFACE SLOPE OF 10.% AND A SLOPE LENGTH OF 1100. FEET.

SCS RUNOFF CURVE NUMBER	=	77.70	
FRACTION OF AREA ALLOWING RUNOFF	=	100.0	PERCENT
AREA PROJECTED ON HORIZONTAL PLANE	=	6.200	ACRES
EVAPORATIVE ZONE DEPTH	=	48.0	INCHES
INITIAL WATER IN EVAPORATIVE ZONE	=	6.981	INCHES
UPPER LIMIT OF EVAPORATIVE STORAGE	=	19.104	INCHES
LOWER LIMIT OF EVAPORATIVE STORAGE	=	6.528	INCHES
INITIAL SNOW WATER	=	0.000	INCHES
INITIAL WATER IN LAYER MATERIALS	=	84.549	INCHES
TOTAL INITIAL WATER	=	84.549	INCHES
TOTAL SUBSURFACE INFLOW	=	0.00	INCHES/YEAR

EVAPOTRANSPIRATION AND WEATHER DATA

NOTE: EVAPOTRANSPIRATION DATA WAS OBTAINED FROM
Selby South Dakota

STATION LATITUDE	=	45.51	DEGREES
MAXIMUM LEAF AREA INDEX	=	3.50	
START OF GROWING SEASON (JULIAN DATE)	=	130	
END OF GROWING SEASON (JULIAN DATE)	=	270	
EVAPORATIVE ZONE DEPTH	=	48.0	INCHES
AVERAGE ANNUAL WIND SPEED	=	10.30	MPH
AVERAGE 1ST QUARTER RELATIVE HUMIDITY	=	71.00	%
AVERAGE 2ND QUARTER RELATIVE HUMIDITY	=	63.00	%
AVERAGE 3RD QUARTER RELATIVE HUMIDITY	=	61.00	%
AVERAGE 4TH QUARTER RELATIVE HUMIDITY	=	69.00	%

NOTE: PRECIPITATION DATA WAS SYNTHETICALLY GENERATED USING
COEFFICIENTS FOR BISMARCK NORTH DAKOTA

NORMAL MEAN MONTHLY PRECIPITATION (INCHES)

JAN/JUL	FEB/AUG	MAR/SEP	APR/OCT	MAY/NOV	JUN/DEC
0.35	0.45	0.87	1.90	2.70	3.23
2.54	1.94	1.36	1.14	0.65	0.38

NOTE: TEMPERATURE DATA WAS SYNTHETICALLY GENERATED USING
COEFFICIENTS FOR BISMARCK NORTH DAKOTA

NORMAL MEAN MONTHLY TEMPERATURE (DEGREES FAHRENHEIT)

JAN/JUL	FEB/AUG	MAR/SEP	APR/OCT	MAY/NOV	JUN/DEC
11.00	18.00	29.00	43.00	56.00	65.00
71.00	70.00	59.00	46.00	29.00	16.00

NOTE: SOLAR RADIATION DATA WAS SYNTHETICALLY GENERATED USING
COEFFICIENTS FOR BISMARCK NORTH DAKOTA
AND STATION LATITUDE = 45.51 DEGREES

****

AVERAGE MONTHLY VALUES IN INCHES FOR YEARS 1 THROUGH 50

	JAN/JUL	FEB/AUG	MAR/SEP	APR/OCT	MAY/NOV	JUN/DEC
PRECIPITATION						
TOTALS	0.38	0.46	0.81	1.70	2.45	3.32
	2.56	1.82	1.47	0.96	0.54	0.42
STD. DEVIATIONS	0.18	0.24	0.46	1.21	1.27	1.40
	1.39	0.81	0.91	0.91	0.36	0.20
RUNOFF						
TOTALS	0.000	0.007	0.022	0.187	0.009	0.003
	0.000	0.000	0.000	0.006	0.001	0.000
STD. DEVIATIONS	0.000	0.030	0.053	0.422	0.025	0.009
	0.000	0.000	0.000	0.043	0.006	0.000
EVAPOTRANSPIRATION						
TOTALS	0.370	0.390	0.420	0.947	2.430	4.649
	3.238	1.799	0.983	0.522	0.269	0.337
STD. DEVIATIONS	0.132	0.150	0.168	0.432	0.413	1.394
	1.462	0.769	0.512	0.204	0.139	0.124
PERCOLATION/LEAKAGE THROUGH LAYER 3						
TOTALS	0.0209	0.0205	0.0243	0.0236	0.0245	0.0218
	0.0215	0.0209	0.0196	0.0201	0.0197	0.0208
STD. DEVIATIONS	0.0265	0.0243	0.0299	0.0291	0.0296	0.0270
	0.0273	0.0280	0.0271	0.0278	0.0266	0.0271

AVERAGES OF MONTHLY AVERAGED DAILY HEADS (INCHES)

DAILY AVERAGE HEAD ON TOP OF LAYER 3

AVERAGES	0.0002	0.0002	0.0002	0.0002	0.0002	0.0002
	0.0002	0.0002	0.0002	0.0002	0.0002	0.0002
STD. DEVIATIONS	0.0003	0.0003	0.0003	0.0003	0.0003	0.0003
	0.0002	0.0003	0.0003	0.0003	0.0003	0.0003

****

****

AVERAGE ANNUAL TOTALS & (STD. DEVIATIONS) FOR YEARS 1 THROUGH 50

	INCHES	CU. FEET	PERCENT
PRECIPITATION	16.89 (2.849)	380049.9	100.00
RUNOFF	0.235 (0.4246)	5279.72	1.389
EVAPOTRANSPIRATION	16.354 (2.7281)	368060.78	96.845
PERCOLATION/LEAKAGE THROUGH LAYER 3	0.25823 (0.31595)	5811.689	1.52919
AVERAGE HEAD ON TOP OF LAYER 3	0.000 (0.000)		
CHANGE IN WATER STORAGE	0.040 (1.4657)	897.56	0.236

****

****

PEAK DAILY VALUES FOR YEARS 1 THROUGH 50

	(INCHES)	(CU. FT.)
PRECIPITATION	2.42	54464.520
RUNOFF	1.282	28857.4023
PERCOLATION/LEAKAGE THROUGH LAYER 3	0.003402	76.55940
AVERAGE HEAD ON TOP OF LAYER 3	0.002	
SNOW WATER	2.11	47559.9180
MAXIMUM VEG. SOIL WATER (VOL/VOL)		0.3075
MINIMUM VEG. SOIL WATER (VOL/VOL)		0.1360

****

****

FINAL WATER STORAGE AT END OF YEAR 50

LAYER	(INCHES)	(VOL/VOL)
1	7.3613	0.1534
2	68.9342	0.1915
3	10.2480	0.4270
SNOW WATER	0.000	

****

****

APPENDIX D

Bearing Capacity Calculations

Soil property assumptions:

Soil cohesion = $c' = 200$ lb/ft^2,

Angle of internal friction = 25 degrees

Soil unit weight = $\gamma = 100$ lb/ft^3

Depth of footing (excavation depth) = $D_f = 6$ ft

Footing width = $B = 1$ ft

Terzaghi's Ultimate Soil Bearing Capacity Equation

$q'_u = 1.3c'N_c + qN_q + 0.4\gamma BN_\gamma$

Bearing capacity factors N_c, N_q, N_γ = 25.13, 12.72, and 8.34 respectively; values are based on 25 degree angle of internal friction (Table 15.1, Das 2002)

$q = D_f\gamma = (6 \text{ ft})\ (100 \text{ lb/ft}^3) = 600 \text{ lb/ft}^2$

$q'_u = (1.3)(200 \text{ lb/ft}^2)(25.13) + (600 \text{ lb/ft}^2)(12.72) + (0.4)(100 \text{ lb/ft}^3)(1 \text{ ft})(8.34)$

$q'_u = 14{,}498.6 \text{ lb/ft}^2$

APPENDIX E

2-D Transport Equation

The concentration at a point x downstream of the source and distance y off centerline of plume at time t is specified as:

$$C(x,y,t) = \frac{C_0}{4}\exp\left[\frac{x}{\alpha_x \cdot 2}\left(1-\sqrt{1+\frac{4\lambda\alpha_x}{\nu}}\right)\right]$$

$$erfc\left[\frac{\left(x-\nu \cdot t\sqrt{1+\frac{4\lambda\alpha_x}{\nu}}\right)}{2\sqrt{\alpha_x \nu t}}\right]\left[erf\left\{\frac{y+\frac{Y}{2}}{2\sqrt{\alpha_y \cdot x}}\right\}-erf\left\{\frac{y-\frac{Y}{2}}{2\sqrt{\alpha_y \cdot x}}\right\}\right]$$

where $\nu = \frac{K \cdot i}{\theta_e \cdot R}$

$C(x,y,t)$ = Concentration at a distance x downstream of the source and distance y off centerline of plume at time t (Concentration units)

C_0 = Concentration in the source zone at time t = 0 (Concentration units)

Y = Line source width (L)

x= Distance downgradient of source (L)

y = transverse distance from the plume centerline (L)

t = Simulation time (T)

α_x = Longitudinal ground-water dispersivity (L/T)

α_y = Transverse ground-water dispersivity (L/T)

λ = First-order degradation rate (1/T)

ν = Ground-water [retarded] seepage velocity

K = Horizontal hydraulic conductivity (L/T)

i = Hydraulic gradient (L/L)

θ = Effective soil porosity

R = Constituent linear retardation factor

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