Solid waste disposal site suitability evaluation in Montana
by David Wayne Bowen

A thesis submitted in partial fulfillment of the requirements for the degree of MASTER OF SCIENCE in Earth Science
Montana State University

Abstract:
Solid waste disposal site suitability studies are needed for understanding potential environmental hazards and for licensing. The Montana Solid Waste Management Bureau identified twenty-one operating sites needing evaluation for solid waste disposal suitability. The sites were evaluated by on-site reconnaissance of soil and hydrogeologic factors. The primary criteria evaluated were permeability of surficial materials, groundwater flow, connection of shallow groundwater with deeper aquifers, and proximity to surface water. In general, a suitable site should be located in materials of low permeability with a deep water table, have no connection of shallow groundwater with deeper aquifers, and should be far from surface water. Fourteen of the twenty-one sites evaluated were unsuitable. Inadequate site suitability assessments were made prior to locating many solid waste disposal sites in Montana. Suitable sites exist within a five mile radius of each of the unsuitable sites. A small amount of data coupled with soil and hydrogeologic planning would lead to better siting.

The site specific studies emphasize the need for generalized soil and hydrogeologic information. Local authorities responsible for solid waste disposal site location must be aware of the constraints which control site suitability in their area. Important soil and hydrogeologic parameters which control site suitability can be categorized on a regional basis for Montana by dividing the state into five physiographic provinces. These five provinces are the Mountains and Valleys, the Unglaciated Plains and Mountains, the Glaciated Plains and Mountains, the Unglaciated Plains, and the Glaciated Plains. In general, unsuitable sites for solid waste disposal in the unglaciated provinces are underlain by alluvium, sandstone, limestone, igneous rocks, or metamorphic rocks; suitable sites are generally underlain by siltstone, claystone, or shale. In the glaciated provinces, unsuitable sites are generally underlain by glacial outwash sands and suitable sites are generally underlain by glacial till.

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Date August 20, 1980

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ABSTRACT

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The site specific studies emphasize the need for generalized soil and hydrogeologic information. Local authorities responsible for solid waste disposal site location must be aware of the constraints which control site suitability in their area. Important soil and hydrogeologic parameters which control site suitability can be categorized on a regional basis for Montana by dividing the state into five physiographic provinces. These five provinces are the Mountains and Valleys, the Unglaciated Plains and Mountains, the Glaciated Plains and Mountains, the Unglaciated Plains, and the Glaciated Plains. In general, unsuitable sites for solid waste disposal in the unglaciated provinces are underlain by alluvium, sandstone, limestone, igneous rocks, or metamorphic rocks; suitable sites are generally underlain by siltstone, claystone, or shale. In the glaciated provinces, unsuitable sites are generally underlain by glacial outwash sands and suitable sites are generally underlain by glacial till.

INTRODUCTION

Many solid waste disposal sites exist in the State of Montana. Relatively few have been assessed for suitability as disposal locations. Isolated site-specific studies at Butte and West Yellowstone, Montana show that contamination of ground and surface water takes place due to the location of solid waste sites in materials which are ill-suited for effective disposal (Kringler, 1979; Jones, 1979). There is a need to evaluate other sites in Montana to assess materials in which they are located for suitability as disposal mediums.

Sites evaluated in the past were evaluated on the basis of the soil at the site and the depth to the water table. These are important parameters which need to be evaluated, however, they are only a part of the integrated hydrogeologic system which controls the suitability of a site. In order to adequately evaluate the suitability for use in solid waste disposal, all parts of the soil and hydrogeologic system must be considered.

To determine a site's suitability for solid waste disposal, it is first necessary to be aware of those parameters which control suitability. With this awareness, a small amount of soil and hydrogeologic data coupled with minimal planning will lead to better siting of solid waste

disposal operations.

Often, local people responsible for siting solid waste disposal operations for their communities are not familiar with those parameters which control a site's suitability, and, are not aware of soil and hydrogeologic relationships in their areas. With this in mind, three main objectives will be met:

1. summarize those parameters which control solid waste disposal site suitability,
2. present the relationship between the soils and hydrogeology at a site and the usefulness of that site for solid waste disposal, and
3. generalize soils and hydrogeologic information pertinent to solid waste disposal for the State of Montana.

These objectives are met by discussing the relationship between soils and hydrogeologic settings and solid waste disposal site suitability. Two sections discuss this relationship. The first section deals with 21 site specific studies in Montana, and conclusions drawn from these studies. The approach to the first section is to provide background information on parameters which control solid waste disposal site suitability, to summarize the results of 21 site specific studies, and to discuss the significance of the results and the associated need for generalized information.

The purpose of the second section is to provide general information useful for directing future site suitability assessments in Montana. This section also generates an awareness of problems related to locating solid waste disposal sites in Montana. The approach to this section is to divide the state into five physiographic provinces and to relate soil and hydrogeologic settings with suitability for solid waste disposal in each of the provinces.

SECTION ONE: SITE SPECIFIC STUDIES

Introduction

The Montana Department of Health and the Environmental Protection Agency recognized that many small landfills exist in the State of Montana for which no site suitability studies have been done. There may be degradation of ground and surface water quality if landfills are located in materials which should not be used for solid waste disposal. Twenty-one disposal sites in Montana were chosen for site specific evaluation by the Montana Department of Health and Environmental Sciences (Figure 1) (Bowen, Custer, and Miller, 1979). The section on site specific studies demonstrates patterns of solid waste disposal site suitability.

The site specific section defines parameters that control suitability. This section uses these parameters to demonstrate the kinds of site suitability problems that exist in Montana. It then shows that hydrogeologic planning is necessary before locating a disposal site, and that only a small amount of general information can lead to much better siting.

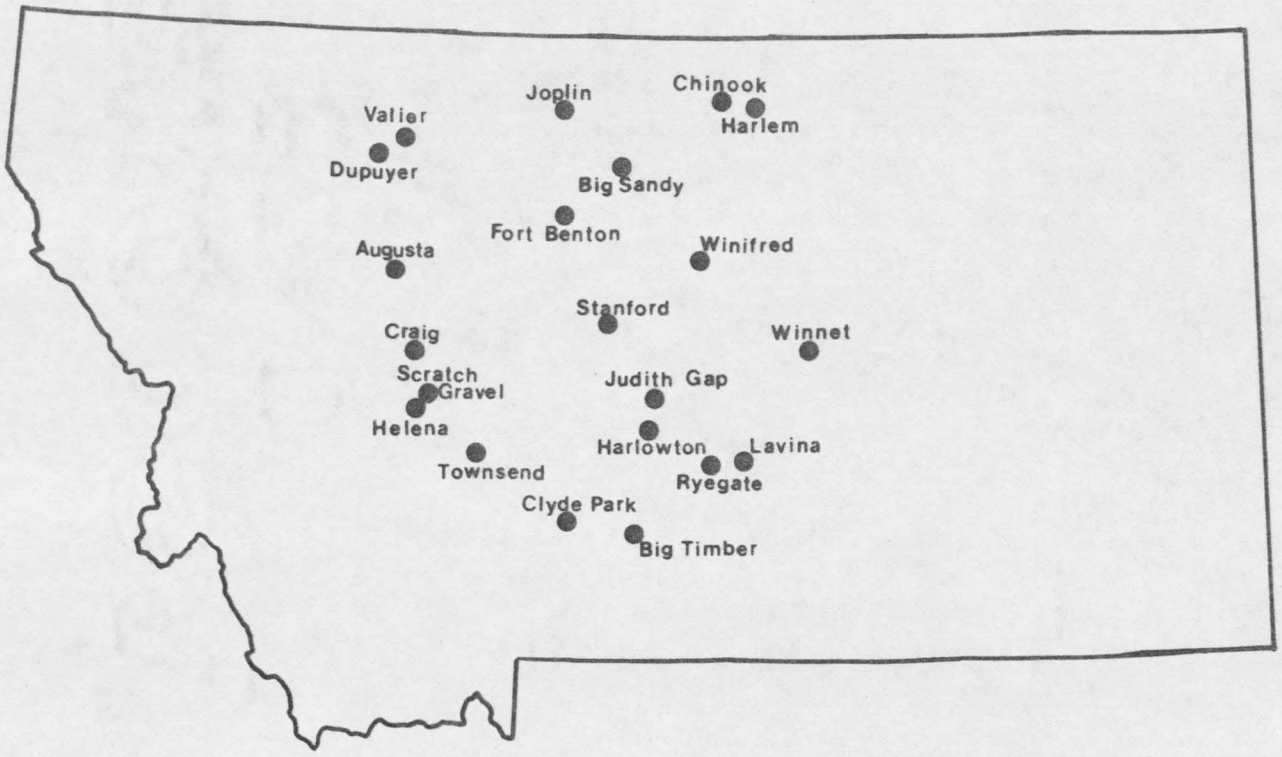

Figure 1: Location map of the 21 site specific studies.

Background Information

Suitability of a site for use as a solid waste disposal site is determined by political, social, economic, climatological, workability, and environmental parameters (Bergstrom, 1968). The study of political, social, economic, and climatological factors is beyond the scope of this study. All of the 21 sites evaluated are in operation. Therefore, workability factors, which include soil texture, soil consistence, stoniness, rockiness, and depth to bedrock (U. S. Soil Conservation Service, 1971), will not be considered further in the site specific section. The evaluated parameters for the 21 chosen sites are all environmental.

The environmental suitability of a solid waste disposal site is dependent upon the ability of the materials in which a site is located to prohibit the production of leachate, or isolate any leachate which is produced at the site (Bergstrom, 1968). Since this is a reconnaissance study, no wells were drilled for monitoring the production and movement of leachate. Thus, several assumptions are necessary. These assumptions are that leachate is produced in a semi-arid climate, and that this leachate is capable of contaminating ground and surface water. Leachate is produced at the West Yellowstone, Montana, and Butte,

Montana landfill sites. This leachate is contaminating ground and surface water (Kringler, 1979; Jones, 1979). Assuming leachate production at landfill sites in Montana, and the capability for contamination of ground and surface water by this leachate, the suitability of a landfill site is controlled by the integrated soil and hydrogeologic system of that site. In general, a suitable site will have impermeable soils and surficial deposits, a deep water table, no connection of shallow groundwater with deeper aquifers, and will be far from surface water (Figure 2). Impermeable soil, when used as a cover material for waste, limits water infiltration and thus the production of leachate. Impermeable surficial deposits help contain leachate to the disposal site. A deep water table lessens the potential for shallow groundwater contamination by leachate. With no connection of shallow groundwater to deeper aquifers the potential for contamination of regional aquifers is eliminated. Finally, a large distance between a disposal site and surface water reduces the potential for contamination of surface water.

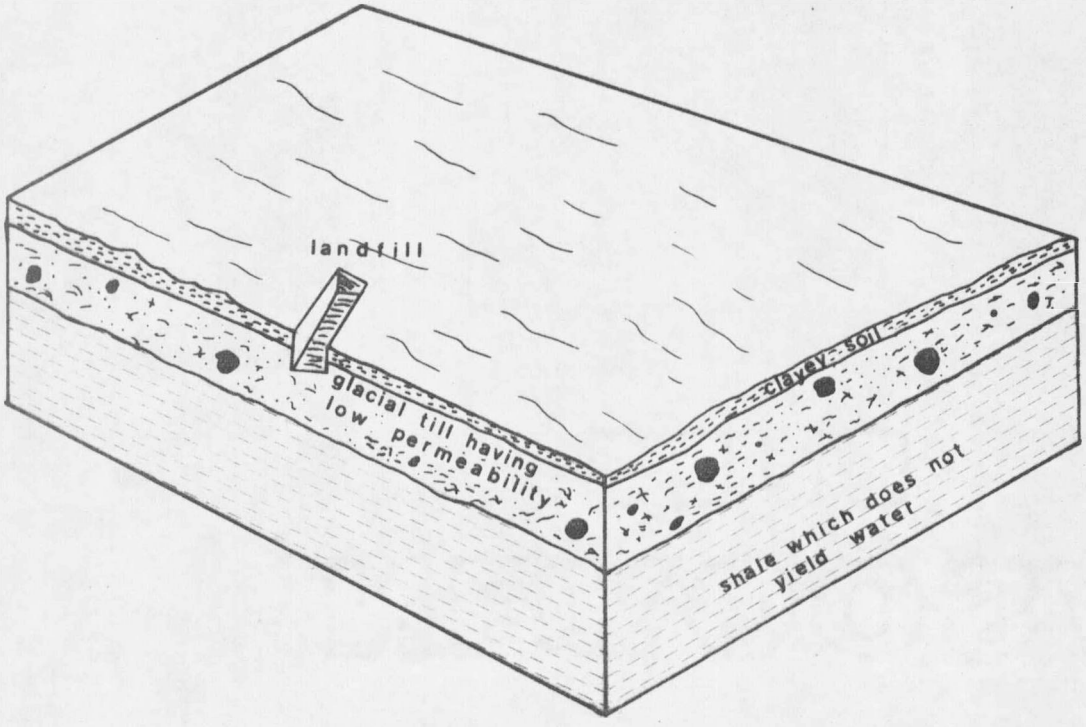

Figure 2: Soils and hydrogeology at a hypothetical suitable, landfill site.

Solid waste disposal sites may be unsuitable for a variety of reasons. A site will not be suitable if it has highly permeable soils and surficial deposits which allow water to infiltrate refuse producing a leachate, and allow this leachate which is produced to escape through the base of the site (Figure 3). A shallow water table beneath the site, which can easily be contaminated by leachate, causes the site to be unsuitable. A site will also be unsuitable if there is a connection between shallow groundwater and deeper aquifers which could lead to contamination from leachate, since, leachate contaminating shallow groundwater could then contaminate deeper aquifers. The other factor which could cause a site to be unsuitable is proximity to surface water, which could lead to contamination of that surface water by leachate.

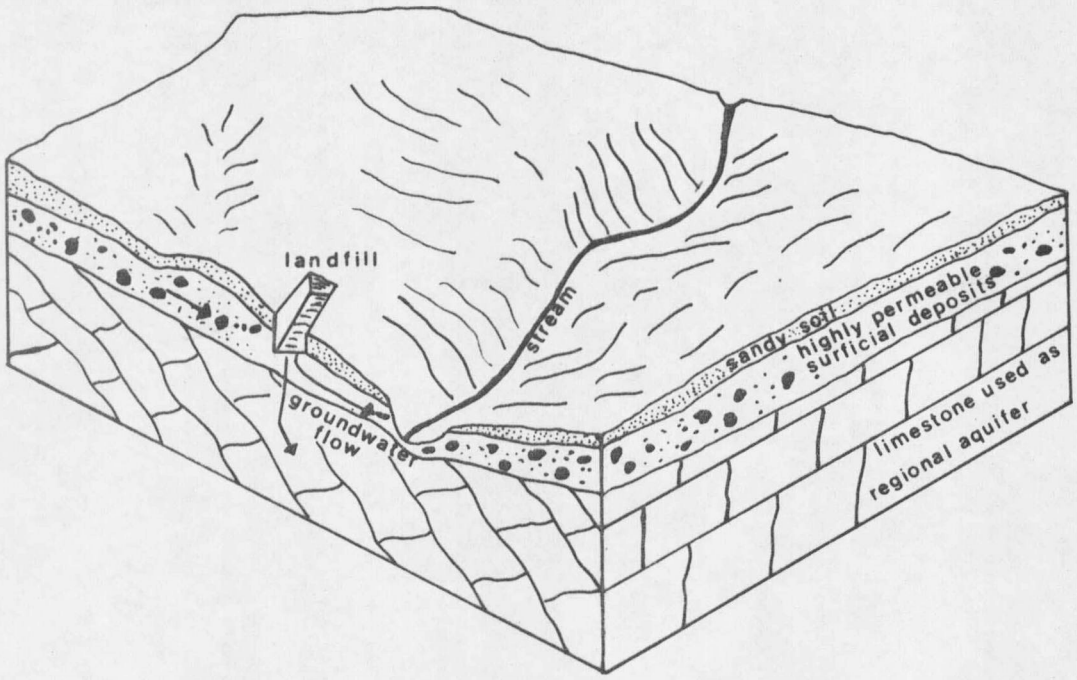

Figure 3: Soils and hydrogeology at a hypothetical, unsuitable landfill site.

In summary, four general criteria are useful for evaluating the environmental suitability of a site:

1. permeability of soils and surficial deposits,
2. depth to shallow groundwater,
3. connection of shallow groundwater with deeper aquifers, and
4. proximity to surface water.

Methods

Field:

soils Operational trenches or backhoe pits were used at each site for soil evaluation. Texture was determined in the field by hand texturing. A field description of the soil included horizonation and thickness. A soil sample from each horizon was collected for lab analysis. Depth to bedrock was measured where exposed.

geology Surficial geologic deposits were determined and described through field observation. Local stratigraphy was described when surface outcrops were present.

hydrology Depth to water table was estimated from vegetative, topographic, and surface water associations. Water table contours were estimated on the basis of topography. Permeabiity was estimated on the basis of soil texture (U.S. Soil Conservation Service, 1971).

Lab:

soils Soil samples were analyzed by hydrometer to determine their texture (Day, 1965). This work was done by the Montana State Soil Testing Lab.

Literature:

geology Available literature was used to determine local stratigraphy and structure, and the aquifer

characteristics of stratigraphic units.

hydrology Regional groundwater flow was found from available literature.

Well Logs:

geology Depth to bedrock and local stratigraphy was found through well logs when applicable logs existed.

hydrology Depth to water table was found through well logs when applicable logs existed.

Results

Limitations of sites for use as sanitary landfills were determined on the basis of the soils and hydrogeologic parameters evaluated at each individual site (Bowen, Custer, and Miller, 1979). The results of the study are summarized in Table 1. The results are discussed following the table.

SITE	TEXTURE	PERMEABILITY	SLOPE	SURFICIAL DEPOSIT	ROCK UNIT	AQUIFER CHARACTERISTICS	DEPTH TO WATER TABLE	POTENTIAL FOR GROUND-WATER CONTAMINATION	POTENTIAL FOR SURFACE WATER CONTAMINATION	LIMITATION
Augusta	loam clay loam	slow to mod. slow	5%	glacial till	Two Medicine Fm	sand units produce water	+100'	slight	slight	slight
Big Sandy	sand loamy sand	rapid	7%	glacial outwash	Claggett Fm	sand units produce water	4'	severe	moderate	severe
Big Timber	loam loamy sand	mod. rapid to rapid	2%	alluvium	unknown	unknown	10-30'	severe	severe	severe
Chinook	sandy loam loamy sand	very rapid	5%	glacial outwash	Judith River Fm	sand units produce water	20'	severe	severe	severe
Clyde Park	loam loamy sand	<84cm slow to +84cm rapid	8%	alluvial fan	Livingston Fm	sand units prod. some water	80'	severe	severe	severe
Craig	loam sandy loam	mod. to mod. rapid	8%	alluvial	volcanics	poor unless fractured	30'	moderate	moderate	moderate
Dupuyer	clay loam sandy loam	<100cm slow, +100cm rapid	3%	glacial till, outwash	Two Medicine Fm	good in the Dupuyer area	8.5'	severe	severe	severe
Fort Benton	clay loam sandy loam	<100cm slow, +100cm rapid	10-25%	colluvium	Colorado shale	very poor	200'	slight	mod. to severe	severe
Harlem	clay loam	slow	2%	glacial till	Bearpaw shale	poor	+100'	slight	slight	slight
Harlowton	clay loam sandy clay	slow to mod. slow	10-15%	alluvium	Judith River Fm	mod., sand units produce water	30-40'	slight	slight	slight
Helena	silt loam sandy loam	rapid	3%	alluvial fan	Tert. basin fill	channel deposits prod. water	30'	severe	severe	severe
Joplin	clay loam silty clay	mod. slow to mod.	2%	glacial till	Colorado shale	very poor	4'	moderate	slight	moderate
Judith Gap	sandy clay sandy loam clay loam	slow, mod. rapid	3.5%	alluvium	Judith River Fm	good in this part of Montana	6'	severe	slight	severe
Lavina	loam sandy loam	mod.	3%	alluvium	Claggett Fm	poor	20'	slight	moderate	moderate
Ryegate	sandy loam	mod. rapid to rapid	2%	absent	Eagle Fm	very good	+50'	moderate	slight	moderate
Scratch Gravel	loam,sandy loam,gravel	slow, rapid	4%	alluvial fan	intrusive igneous	poor unless fractured	35-60'	severe	slight	severe
Stanford	loam,sandy loam & clay	slow to very slow	7%	alluvial	Colorado shale	very poor	20'	slight	slight	slight
Townsend	sandy loam sand	slow<85cm, rapid 85+	8%	alluvial fan	Madison ls.	very good	30-150'	severe	moderate	severe
Valier	clay loam clay	very slow	2%	glacial till	Two Medicine Fm	sand units produce water	+50'	slight	slight	slight
Vinifred	sandy loam clay loam	<70cm mod. +70cm slow	1%	alluvium	Judith River Fm	sand units produce water	15'	slight	severe	severe
Winnet	sandy clay loam	mod.	3%	alluvium	Colorado shale	very poor	+50'	slight	slight	slight

Table 1: Summary of environmental parameters evaluated and suitability results for 21 evaluated landfill sites.

Discussion of Results

Evaluated sites were given suitability limitation ratings on the basis of potential for ground or surface water contamination by leachate from the sites. Since the studies did not include actual measurements of leachate production or movement, suitability limitation ratings were designated on the probability of contamination based on the soil and hydrogeologic parameters evaluated at each site. A site has a slight limitation if the soil and surficial deposit is of low permeability, the groundwater table is deep, shallow groundwater beneath the site is not connected with deeper aquifers, and the site is far from surface water. A site has a severe limitation if it is likely to cause contamination of ground or surface water. This contamination problem can be due to high permeability of soil and surficial deposits, a shallow groundwater table, a connection of shallow groundwater with deeper aquifers, or the site being close to surface water. A site has a moderate limitation if the site is less than ideal, but, is not clearly seen to be a potential source for contamination of ground or surface water. An example of this situation would be a site that is close to surface water, which would normally cause a severe limitation, but has soil and surficial deposits of very low permeabilities mitigating the

contamination problem.

Seven of the 21 sites evaluated were determined suitable for solid waste disposal. The Augusta solid waste disposal site is an example (Table 1). The Augusta disposal site is in sandy-clay-loam and loam soil. The soil is developed from clayey glacial till and has low permeability. Groundwater is first encountered 100' below the landfill in a sand unit of the Two Medicine Formation (Figure 4). Relatively impermeable till and shale separate the disposal site from groundwater so there is little chance of groundwater contamination by leachate. The site is far from surface water, separated by gently rolling topography; there is little potential for surface water contamination.

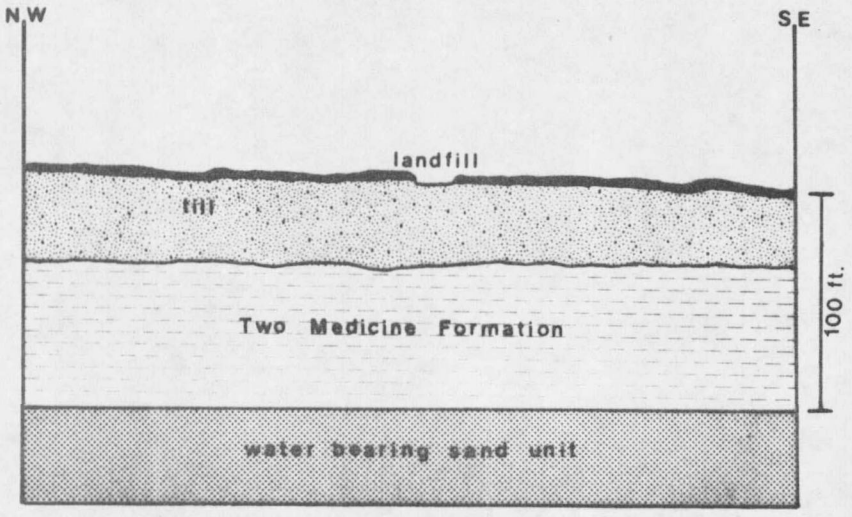

Figure 4: Generalized cross-section through the Augusta solid waste disposal site.

Fourteen of the sites were unsuitable for use as sanitary landfills. Sites were unsuitable for four reasons.

1. high permeability of soils and surficial deposits,
2. shallow groundwater flow through, or near, the base of a site,
3. connection of shallow groundwater beneath the site, with deeper aquifers,
4. proximity to surface water.

Examples of each type of problem are presented in the following paragraphs.

The Helena, Montana landfill site is an unsuitable disposal site due to the high permeability of surficial materials (Figure 5). Helena's landfill site is in sand and sandy loam soils having rapid permeability (Table 1). The surficial deposits at the Helena landfill site are alluvial fan deposits consisting of sands, gravels, and cobbles. This material has rapid permeability below the soil zone. The highly permeable nature of the surficial materials allows water to readily infiltrate refuse producing a leachate, and allows this leachate to leave the site through the base. The water table is 30' below the surface and a small stream discharges from the landfill through a culvert at the northeast end of the landfill site. The high permeability of surficial materials leads to a severe potential for ground and surface water contamination.

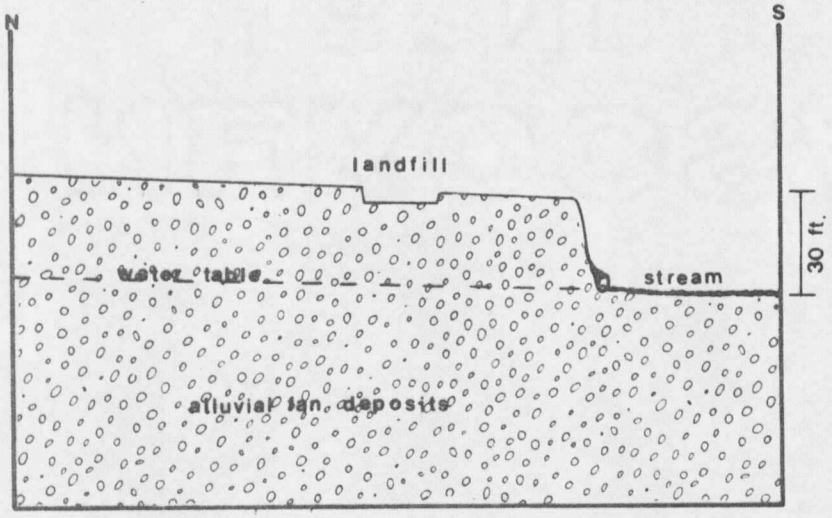

Figure 5: Generalized cross-section through the Helena solid waste disposal site.

The landfill at Big Sandy, Montana is unsuitable because shallow groundwater flows through the base of the site (Figure 6). The Big Sandy landfill site is in sand and sandy loam soil (Table 1). The surface is veneered with 7 feet of glacial outwash sands overlying glacial till. Shallow groundwater is ponded above the glacial till and flows down the hydrologic (topographic) gradient through the sands. Refuse floats on water at the landfill site producing leachate. This leachate is transmitted away from the site in the shallow groundwater. Due to the severe potential for groundwater contamination the Big Sandy landfill site is unsuitable for use.

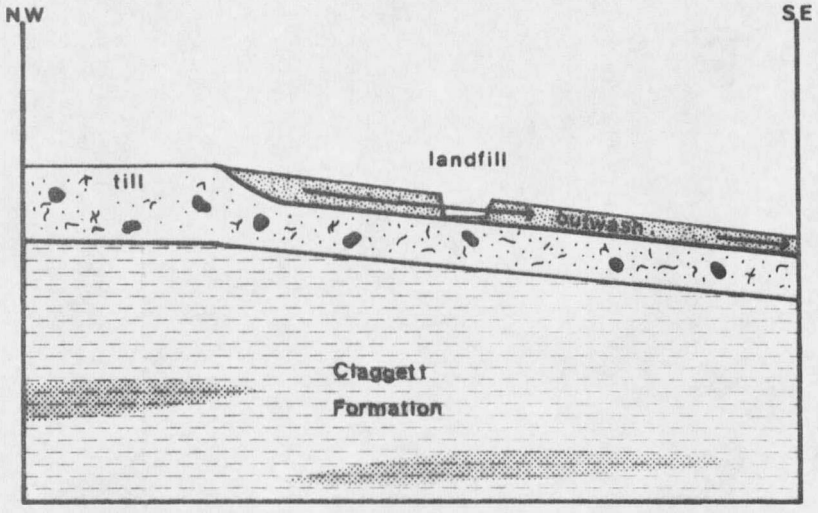

Figure 6: Generalized cross-section through the Big Sandy solid waste disposal site.

The landfill site at Judith Gap, Montana is unsuitable because of the connection between shallow groundwater and deeper aquifers under the site. (Figure 7). Field observation at the Judith Gap site shows a water table 6 feet below the surface and the Judith River Formation 7 feet below the surface. In the Judith Gap area the Judith River Formation is a sandstone which acts as a good aquifer (Groff, 1962). Shallow groundwater flowing through the base of the landfill will produce a leachate. This leachate will flow down gradient with the shallow groundwater and flow into the Judith River Formation, leading to a severe potential for contamination of that aquifer.

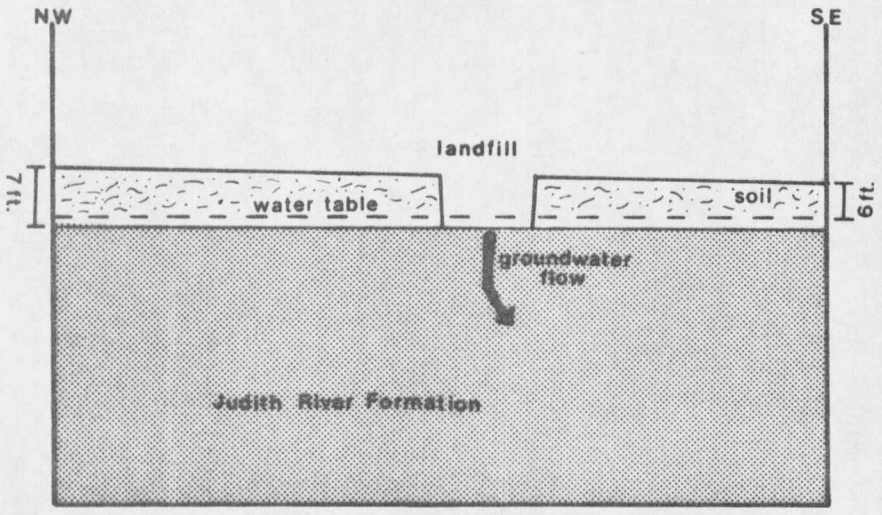

Figure 7: Generalized cross-section through the Judith Gap solid waste disposal site.

The Dupuyer, Montana landfill site is unsuitable due to a severe potential for contamination of surface water (Figure 8). The Dupuyer landfill site is in clay loam soil (Table 1). The surface is veneered with 5' of glacial till underlain by glacial outwash sands. The water table at the landfill site is 8.5 feet below the surface with the base of the landfill trench below the water table. Shallow groundwater flowing through the refuse leaches out contaminants and carries them down the hydrologic (topographic) gradient into Dupuyer Creek where shallow groundwater is discharged. Due to the severe potential for surface water contamination the Dupuyer site is unsuitable.

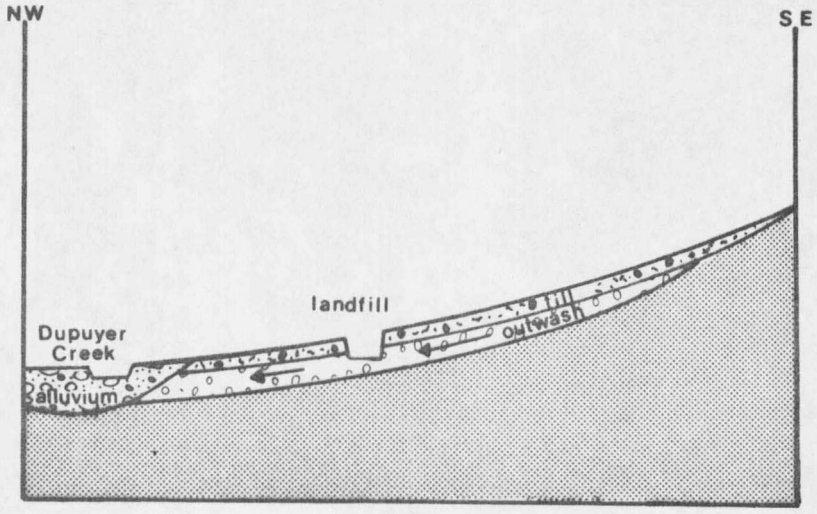

Figure 8: Generalized cross-section through the Dupuyer solid waste disposal site.

A site-suitability pattern emerged from these studies (Table 2). Suitability is strongly related to the geologic medium into which refuse is disposed. Those sites using a similar geologic medium for disposal generally have similar suitabilities.

Alluvium is usually unsuitable as in general it has high permeabilities, is close to surface water, and is found in association with shallow groundwater. Glacial outwash sands are usually unsuitable. Glacial outwash sands have rapid permeabilities and are associated with shallow groundwater. Sandstone is also generally unsuitable, as sandstone units are aquifers over much of Montana. Disposal sites located over sandstone units could easily transmit leachate into the associated aquifers.

Sites located in glacial till are generally suitable. Glacial till has low permeabilities which tend to contain leachate at the site area. Till fracturing may increase the permeability (Grisak and others, 1976) and could lead to severe limitations for sites located in the fractured till.

Disposal Medium	Limitations		
	Severe	Moderate	Slight
alluvium	7	2	3
glacial outwash	3	0	0
sandstone	1	1	0
glacial till	0	0	4

Table 2: Site suitability patterns. The disposal mediums are listed on the left. The three columns represent the three limitation ratings. The numbers in these columns signify the number of sites having an assigned limitation for that disposal medium.

Inadequate site suitability assessments were made in the past. Fourteen out of the twenty-one sites evaluated were unsuitable. Only a small amount of data and minimal hydrogeologic planning would have been necessary to place these sites in suitable locations. All fourteen of the unsuitable sites had suitable locations within a 5 mile radius of the unsuitable site.

The landfill at Judith Gap, Montana is an example which shows the necessity for hydrogeologic planning before disposal site location. The landfill site at Judith Gap is unsuitable due to a potential for connection of shallow groundwater with deeper aquifers as previously discussed. The geologic units of concern at the Judith Gap landfill site are the Judith River Formation, the Claggett Formation, the Eagle Sandstone, and the Colorado Shale (Figure 9).

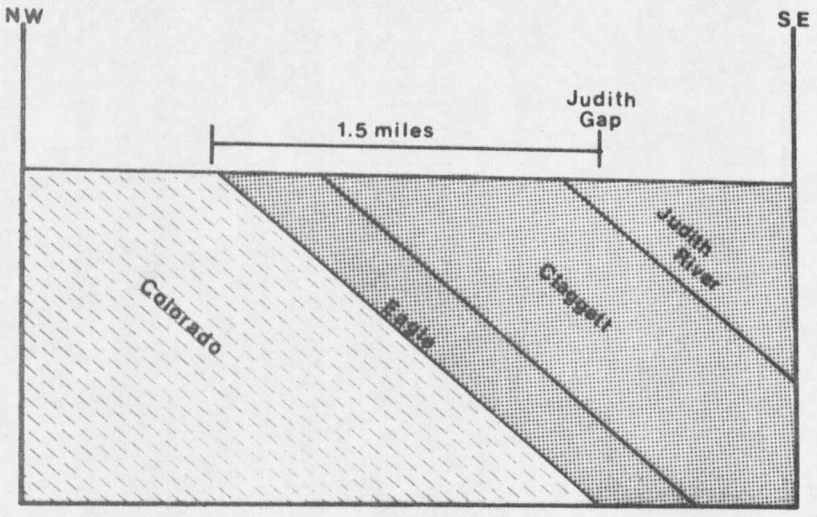

Figure 9: Generalized NW-SE cross-section in the Judith Gap area.

All four of these units trend northeast-southwest and dip to the southeast (Groff, 1962). The Judith River Formation, Claggett Formation, and Eagle Sandstone are all sandstone units and act as good aquifers in this part of Montana (Groff, 1962). The Colorado Shale has very poor water bearing characteristics (Groff, 1962). Solid waste disposal sites should avoid any of the three sandstone units because of the potential for contamination of their associated aquifers. The Colorado Shale, however, is a good geologic unit on which to place disposal sites as the soils developed on the Colorado Shale are generally deep and impermeable (Veseth, 1980), and the unit is not an aquifer. The Colorado Shale is found at the surface 1.5 miles to the northwest of the existing Judith Gap landfill site (Figure 9). A site located over the Colorado Shale would most likely be suitable.

Conclusions

Inadequate site suitability assessments were made before locating many solid waste disposal sites in Montana. Fourteen out of twenty-one sites evaluated were unsuitable. Only a small amount of data and minimal hydrogeologic planning would have been necessary to place these sites in suitable locations. Suitable locations exist within a five mile radius of each of the unsuitable sites. A general knowledge of soils and hydrogeology in an area coupled with a small amount of planning would lead to better placement of solid waste disposal sites. The following section will generalize soil and hydrogeologic information helpful in planning future solid waste disposal sites in Montana.

SECTION TWO: RELATIONS OF SOIL AND HYDROGEOLOGIC SETTINGS TO SOLID WASTE DISPOSAL SITE SUITABILITY IN MONTANA

Introduction

The site studies show that inadequate site suitability assessments were made before locating many existing solid waste disposal sites in Montana. Generalized information on Montana's soils and hydrogeology will help direct future siting in specific ways. The information creates an awareness of how local materials relate to the location of suitable solid waste disposal sites. The information also helps to identify disposal problems which might be expected in a given area. The following section will provide this generalized information on soils and hydrogeology as it relates to solid waste disposal in Montana.

The suitability of a site for the disposal of solid wastes is controlled by the integrated system of the soils and hydrogeology at the site. The soils and hydrogeology in a given area are determined by the geologic history of an area and the resultant geologic relationships. These geologic relationships will determine the physiography of the area. Areas with similar physiographies have comparable soil and hydrogeologic properties, and therefore have similar suitability characteristics for solid waste disposal.

Montana can be divided into five physiographic provinces

(Figure 10).

1. Mountains and Valleys
2. Plains and Mountains Unglaciated
3. Plains and Mountains Glaciated
4. Plains Unglaciated
5. Plains Glaciated

Each of these provinces have characteristic soil and hydrogeologic relationships resulting from the geologic history within the province. Suitability for solid waste disposal is dependent upon the soil and hydrogeologic relationships. It may be noted that Fenneman's (1931) classification of physiographic provinces is not used. This is because Fenneman's classification deals with the western United States as a whole and is not specific enough for the purpose of this paper.

This section develops each of the five physiographic provinces according to the following format:

1. geographic setting The geographic setting describes general physical characteristics and the boundary of the province.

2. general geologic setting The general geologic setting provides generalized background information on the geologic history of the province and the resultant geologic relationships.

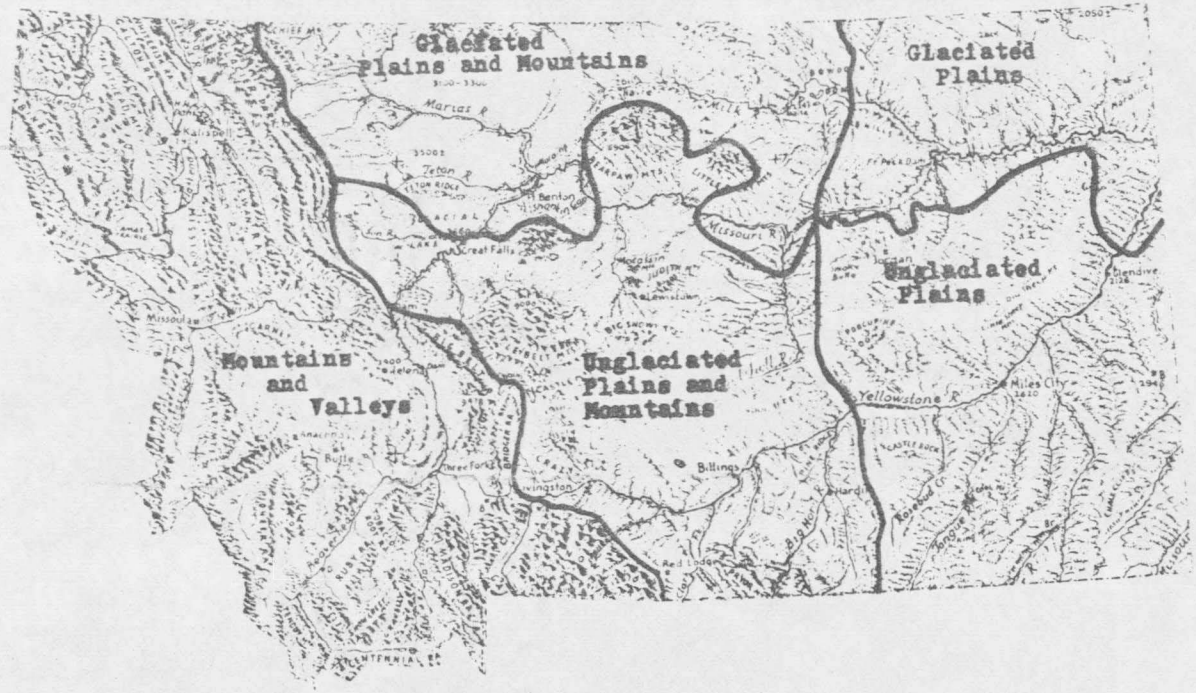

Figure 10: Physiographic map of Montana.
(modified from Raisz, 1952)

3. hydrogeologic units and water bearing characteristics The section discusses the hydrogeologic units found in the province and the water bearing characteristics of these units.

4. soils The soils section discusses the soils developed on the hydrogeologic units and the properties of these soils as related to the disposal of solid wastes.

5. suitability patterns The section on suitability patterns discusses those properties associated with each hydrogeologic unit in the province which relates to suitability for solid waste disposal.

6. summary This section summarizes disposal mediums which should be avoided and disposal mediums which are generally suitable in the province.

There is some redundancy of information between physiographic province chapters. This is intentional as each chapter is written as a complete unit which can be read without reference to other chapters, to aid readers interested only in a specific region.

Mountains and Valleys Province

Geographic Setting

The Mountains and Valleys Province consists of a linear group of northwest-southeast mountains separated by broad intermontane basins (Figure 11). The boundary of the province is the Montana-Canada border to the north, the Montana-Idaho border to the west, the Montana-Wyoming border to the south, and the change in relief associated with the Plains and Mountains Province to the east.

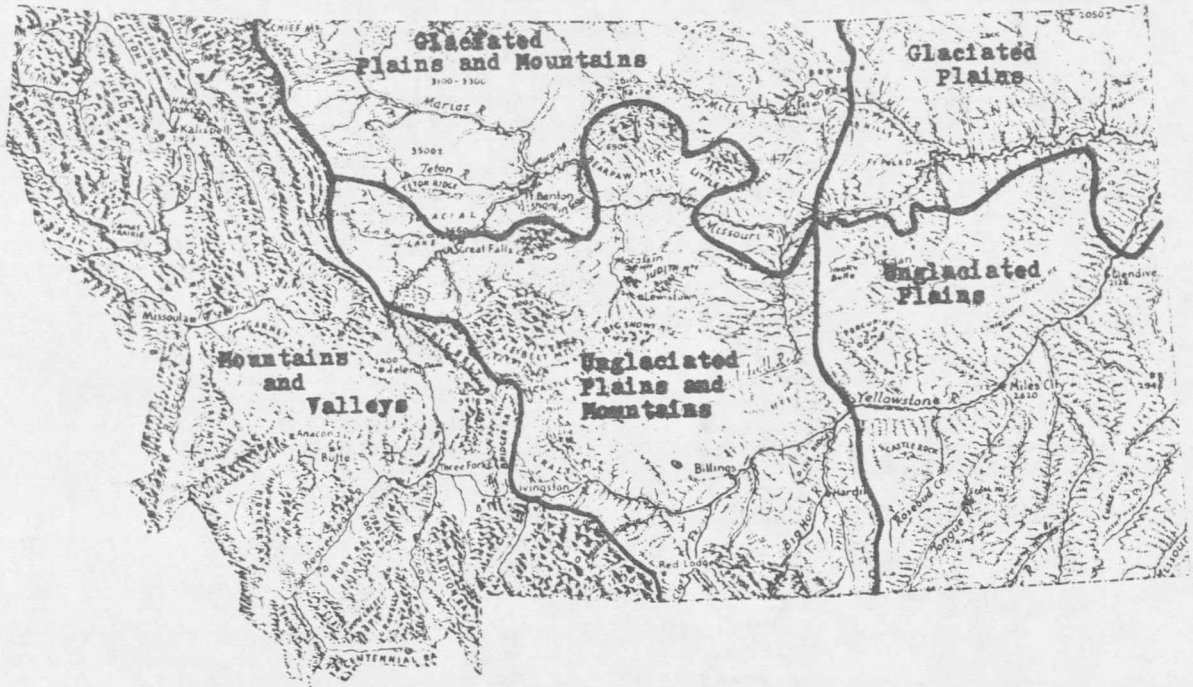

Figure 11: Location map of the Mountains and Valleys Province. (modified from Raisz, 1952)

General Geologic Setting

The Mountains and Valleys Province has a long geologic history. Compression during the Laramide Orogeny folded and faulted the Rocky Mountains in late Cretaceous and early Tertiary time. Erosion during early Tertiary time modified these mountains and filled the valleys with sediment. Tertiary/Cretaceous igneous rocks (Figure 12; Tkv, Tki) are sporadically dispersed throughout the Mountains and Valleys Province, the result of igneous activity associated with the Laramide Orogeny. Tensional block faulting began to lift mountains and drop valleys in middle Tertiary time and continues today. These movements temporarily blocked river drainages and the valleys filled with sediments from the erosion of adjacent mountains (TQu; Figure 12). At times, rivers flowed across the basins leaving channel sand and gravel deposits interbedded with the silt and clay deposits of blocked drainages (Hughes, 1980; Kuenzi and Fields, 1971; Robinson, 1963, 1961). Quaternary fluvial and eolian processes resulted in the deposition of alluvial fan, river, terrace, and loess deposits (TQu) over the Tertiary basin fill deposits. Mesozoic and Paleozoic sedimentary rocks (Km, Kc, KJTr, MP, DЄ) are found on the flanks and on the tops of uplifted blocks in southwest Montana. Precambrian metasediments (pЄb, pЄbl, pЄbu) are widespread in north-