Hydrogeology of surficial, unconsolidated quaternary aquifers, Maynard Creek catchment, Bridger Range, Montana
by John F Whittingham

A thesis submitted in partial fulfillment of the requirements for the degree of Master of Science in Earth Sciences
Montana State University
© Copyright by John F Whittingham (1996)

Abstract:
The groundwater regime within the Maynard Creek catchment is poorly defined. Aquifers may exist in fractured bedrock and surficial, unconsolidated Quaternary deposits. Ski area and residential development within the catchment has increased water demands. This investigation addresses the following questions: 1) Do the surficial, unconsolidated Quaternary deposits function as aquifers?; 2) Can surficial aquifer discharge be distinguished from bedrock aquifer discharge?; and 3) Can the surficial aquifers be characterized? The techniques used in this investigation include: 1) geologic mapping; 2) stream hydrograph and flow duration curve analyses; 3) groundwater discharge monitoring; 4) hydrogeochemical analyses; 5) material sampling; and 6) seismic refraction.

Geologic mapping was completed to delineate potential aquifers. Groundwater discharge features, including 62 springs, are strongly clustered within surficial deposits. Most springs and seeps, and all perennial streamflow exist at lower elevations where surficial deposits are thickest. Stream hydrograph analyses indicate that discharge is sustained by direct surface water runoff and that groundwater discharge is limited.

Springs within surficial deposits display rapidly increased yields after intense precipitation and snowmelt runoff. Three perennial springs exist and each discharges from surficial deposits. These springs yield between 3 lps (0.1 cfs) and 28 lps (1.0 cfs).

Spring water temperatures decrease with increased elevation by 1.0° (1.8°F) per 100 m (328 ft). Groundwater discharges from surficial deposits have low winter temperatures (2 to 4°C, 36 to 39°F) that steadily increase through the summer. The average temperature variability of the most persistent surficial springs is 1.9°C (3.4°F). Water temperatures of bedrock springs are higher (5.0°C, 41°F), with an average variability of 0.2°C (0.4°F). Water temperatures of discharge from surficial deposits are rapidly depressed 0.1 to 1.0°C (0.2 to 1.8°F) by meteorological and snowmelt runoff events. The most productive perennial spring's annual water temperature cycle mimics the annual mean daily air temperature cycle with a lag time of 60 days.

Specific electrical conductance of all 62 spring waters was 0.16 to 0.50 (mS). This indicates low ionic concentrations of total dissolved solids and short residence times for stored groundwater. Springs flowing from surficial deposits discharge Ca (calcium) and HCO₃ (bicarbonate) enriched waters. Well waters derived from bedrock are Na (sodium) and HCO₃ (bicarbonate) enriched.

Material sampling and seismic refraction indicate that rock glacier till, undifferentiated till, outwash, and buried channels are the primary components of surficial aquifers. Porosity, storativity, and hydraulic conductivity were approximated for Quaternary materials. Rock glacier till, outwash, and buried channels yield rapid and intermittent groundwater discharge. Undifferentiated tills sustain perennial stream baseflows. The surficial Quaternary aquifers have development potential, but excessive winter withdrawals will reduce perennial stream baseflows.
HYDROGEOLOGY OF SURFICIAL, UNCONSOLIDATED QUATERNARY AQUIFERS, MAYNARD CREEK CATCHMENT, BRIDGER RANGE, MONTANA

by

John F. Whittingham

A thesis submitted in partial fulfillment of the requirements for the degree of Master of Science in Earth Sciences

MONTANA STATE UNIVERSITY
Bozeman, Montana

May 1996
APPROVAL

of a thesis submitted by

John Frederic Whittingham

This thesis has been read by each member of the thesis committee and has been found to be satisfactory regarding content, English usage, format, citations, bibliographic style, and consistency, and is ready for submission to the College of Graduate Studies.

21 Jan 1996
Date

Chairperson, Graduate Committee

Approved for the Major Department

21 Jan 1996
Date

Head, Major Department

Approved for the College of Graduate Studies

3/2/96
Date

Head, Graduate Dean
STATEMENT OF PERMISSION TO USE

In presenting this thesis (paper) in partial fulfillment of the requirements for a master's degree at Montana State University, I agree that the Library shall make it available to borrowers under the rules of the Library.

If I have indicated my intention to copyright this thesis (paper) by including a copyright notice page, copying is allowable only for scholarly purposes, consistent with "fair use" as described in the U.S. Copyright Law. Requests for permission for extended quotations from or reproduction of this thesis (paper) in whole or in parts may be granted only by the copyright holder.

Signature [Signature]
Date [Jan. 21 1996]
IV

VITA

John Frederic Whittingham was born to David and Helen Whittingham in Williamsburg, Virginia on November 6, 1959. He attended elementary through high school grades in Colorado Springs, Colorado, and graduated from Thomas B. Doherty High School in 1977. Mr. Whittingham attended the University of Colorado in Boulder from 1977 to 1979 and participated in general studies and Earth Sciences. Between 1979 and 1981, Mr. Whittingham completed Emergency Medical Technician certification at Pikes Peak Community College in Colorado Springs, and pursued Ski Area Management and avalanche studies at Colorado Mountain College, in Leadville and Breckenridge, Colorado. He was a member of the El Paso County, Colorado, Search and Rescue between 1979 and 1981. In 1981, Mr. Whittingham enrolled at the University of Montana in Missoula. In 1986, he completed a B.A. in Geology with a professional emphasis in Hydrogeology, and a B.A. in Geography with a corollary field in Watershed Management. Mr. Whittingham worked as a teacher, builder, and geologist from 1986 to 1990. In 1990, Mr. Whittingham initiated graduate studies in Earth Sciences at Montana State University, in Bozeman. He completed a M.S. in Earth Sciences in 1996. He also completed the Center for High Elevation Studies program requirements at Montana State University. In 1992, Mr. Whittingham worked as a hydrologist technician for the United States National Forest Service, Beaverhead National Forest, in Dillon, Montana. In 1993, Mr. Whittingham began permanent employment as a hydrologist with the Bureau of Land Management, Dillon Resource Area, in Dillon, Montana. Mr. Whittingham is currently employed (1996) by the Bureau of Land Management in Dillon, where he administers the Soil, Water, and Air, and Hazardous Materials Programs.
# TABLE OF CONTENTS

<table>
<thead>
<tr>
<th>Section</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>LIST OF TABLES</td>
<td>v</td>
</tr>
<tr>
<td>LIST OF FIGURES</td>
<td>vi</td>
</tr>
<tr>
<td>LIST OF PLATES</td>
<td>xi</td>
</tr>
<tr>
<td>ABSTRACT</td>
<td>xii</td>
</tr>
<tr>
<td>INTRODUCTION</td>
<td>1</td>
</tr>
<tr>
<td>Geographic Setting</td>
<td>3</td>
</tr>
<tr>
<td>Structural Geology</td>
<td>3</td>
</tr>
<tr>
<td>Stratigraphy</td>
<td>6</td>
</tr>
<tr>
<td>Hydrogeologic Setting</td>
<td>6</td>
</tr>
<tr>
<td>Hydrologic Setting</td>
<td>9</td>
</tr>
<tr>
<td>The Problem</td>
<td>10</td>
</tr>
<tr>
<td>Purpose</td>
<td>10</td>
</tr>
<tr>
<td>METHODS</td>
<td>11</td>
</tr>
<tr>
<td>Mapping</td>
<td>11</td>
</tr>
<tr>
<td>Aerial Photographs and Existing Maps</td>
<td>11</td>
</tr>
<tr>
<td>Geologic Mapping</td>
<td>12</td>
</tr>
<tr>
<td>Geomorphologic Mapping</td>
<td>13</td>
</tr>
<tr>
<td>Hydrogeologic Mapping</td>
<td>14</td>
</tr>
<tr>
<td>Aquifer Material Characterization</td>
<td>15</td>
</tr>
<tr>
<td>Surficial Materials and Potential Aquifers</td>
<td>15</td>
</tr>
<tr>
<td>Existing Research</td>
<td>16</td>
</tr>
<tr>
<td>Seismic Refraction</td>
<td>16</td>
</tr>
<tr>
<td>Site Examination</td>
<td>17</td>
</tr>
<tr>
<td>Hydrology</td>
<td>18</td>
</tr>
<tr>
<td>Existing Data</td>
<td>18</td>
</tr>
<tr>
<td>Stream Discharge Measurements</td>
<td>18</td>
</tr>
<tr>
<td>Water Chemistry</td>
<td>19</td>
</tr>
<tr>
<td>Existing Data</td>
<td>19</td>
</tr>
<tr>
<td>Field and Laboratory Methods</td>
<td>19</td>
</tr>
<tr>
<td>Spring Water Monitoring</td>
<td>20</td>
</tr>
<tr>
<td>Spring Inventory and Monitoring</td>
<td>20</td>
</tr>
<tr>
<td>Spring Discharge</td>
<td>21</td>
</tr>
<tr>
<td>Specific Electrical Conductance</td>
<td>22</td>
</tr>
<tr>
<td>Spring Water Temperatures</td>
<td>22</td>
</tr>
</tbody>
</table>
# TABLE OF CONTENTS - Continued

<table>
<thead>
<tr>
<th>RESULTS</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mapping</td>
<td>23</td>
</tr>
<tr>
<td>Geologic Mapping</td>
<td>23</td>
</tr>
<tr>
<td>Geomorphologic Mapping</td>
<td>28</td>
</tr>
<tr>
<td>Hydrogeologic Mapping</td>
<td>35</td>
</tr>
<tr>
<td>Aquifer Material Characterization</td>
<td>37</td>
</tr>
<tr>
<td>Surficial Materials and Potential Aquifers</td>
<td>37</td>
</tr>
<tr>
<td>Existing Research</td>
<td>37</td>
</tr>
<tr>
<td>Seismic Refraction</td>
<td>37</td>
</tr>
<tr>
<td>Site Examination</td>
<td>45</td>
</tr>
<tr>
<td>Hydrology</td>
<td>49</td>
</tr>
<tr>
<td>Existing Data</td>
<td>49</td>
</tr>
<tr>
<td>Stream Discharge Measurements</td>
<td>54</td>
</tr>
<tr>
<td>Water Chemistry</td>
<td>55</td>
</tr>
<tr>
<td>Existing Data</td>
<td>55</td>
</tr>
<tr>
<td>New Data</td>
<td>57</td>
</tr>
<tr>
<td>Spring Water Monitoring</td>
<td>57</td>
</tr>
<tr>
<td>Spring Inventory and Monitoring</td>
<td>57</td>
</tr>
<tr>
<td>Spring Discharge</td>
<td>58</td>
</tr>
<tr>
<td>Specific Electrical Conductance</td>
<td>58</td>
</tr>
<tr>
<td>Spring Water Temperatures</td>
<td>60</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>INTERPRETATIONS</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Surficial, Unconsolidated Quaternary Aquifers</td>
<td>62</td>
</tr>
<tr>
<td>Interpretation of Mapping Results</td>
<td>62</td>
</tr>
<tr>
<td>Hydrograph Analyses</td>
<td>67</td>
</tr>
<tr>
<td>Spring Water Temperatures</td>
<td>70</td>
</tr>
<tr>
<td>Surficial Quaternary Aquifers and Bedrock Aquifers</td>
<td>77</td>
</tr>
<tr>
<td>Field Interpretations</td>
<td>77</td>
</tr>
<tr>
<td>Chemical Interpretations</td>
<td>78</td>
</tr>
<tr>
<td>Spring Water Monitoring Interpretations</td>
<td>82</td>
</tr>
<tr>
<td>Characterization of Surficial, Unconsolidated Quaternary Aquifers</td>
<td>85</td>
</tr>
<tr>
<td>Quaternary Deposits that Do Not Function as Aquifers</td>
<td>85</td>
</tr>
<tr>
<td>Glacial Deposits as Aquifers</td>
<td>87</td>
</tr>
<tr>
<td>Bridger Aquifer</td>
<td>91</td>
</tr>
<tr>
<td>Deer Park Aquifer</td>
<td>95</td>
</tr>
<tr>
<td>Groundwater Development</td>
<td>103</td>
</tr>
</tbody>
</table>

| CONCLUSION                                   | 108  |
| APPENDIX 1                                   | 115  |
| REFERENCES CITED                             | 123  |
# LIST OF TABLES

<table>
<thead>
<tr>
<th>Table</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Published Estimated Values of Porosity, Storativity, and Hydraulic Conductivity for Unconsolidated Materials</td>
<td>38</td>
</tr>
<tr>
<td>2. Seismic Velocities and Calculated Depths of Materials in the Maynard Catchment</td>
<td>42</td>
</tr>
<tr>
<td>3. Published Seismic Velocities of Geologic Materials</td>
<td>43</td>
</tr>
<tr>
<td>4. The Range and Average Seismic Velocities of Specific Geologic Materials in the Maynard Creek Catchment</td>
<td>46</td>
</tr>
<tr>
<td>5. Calculated Monthly Discharge of Maynard Creek</td>
<td>51</td>
</tr>
<tr>
<td>6. Chemical Analyses of Waters Collected from Wells Located in the Maynard Creek Catchment</td>
<td>55</td>
</tr>
<tr>
<td>7. Chemical Analyses of Waters Collected from Springs and Creeks from Within or Near the Maynard Creek Catchment</td>
<td>56</td>
</tr>
<tr>
<td>8. Chemical Analyses of Waters Collected from Perennial Springs in the Maynard Creek Catchment</td>
<td>57</td>
</tr>
<tr>
<td>9. Ionic Balance of Chemical Analyses Used During this Investigation</td>
<td>80</td>
</tr>
<tr>
<td>10. Inferred Values of Porosity, Storativity, and Hydraulic Conductivity for Surficial, Unconsolidated Quaternary Materials Inspected in the Maynard Creek Catchment</td>
<td>103</td>
</tr>
<tr>
<td>Figure</td>
<td>Page</td>
</tr>
<tr>
<td>--------</td>
<td>------</td>
</tr>
<tr>
<td>1.</td>
<td>The Bridger Range and Maynard Creek Catchment</td>
</tr>
<tr>
<td>2.</td>
<td>Topographic Map of the Maynard Creek Catchment</td>
</tr>
<tr>
<td>3.</td>
<td>Generalized Stratigraphic Section</td>
</tr>
<tr>
<td>4.</td>
<td>The Bridger Groundwater Discharge Investigation Area</td>
</tr>
<tr>
<td>5.</td>
<td>The Deer Park Groundwater Discharge Investigation Area</td>
</tr>
<tr>
<td>6.</td>
<td>Time-Distance Diagram for Seismic Line 8: Depiction of a Two-Layer Stratigraphy</td>
</tr>
<tr>
<td>7.</td>
<td>Time-Distance Diagram for Seismic Line 17: Depiction of a Three-Layer Stratigraphy</td>
</tr>
<tr>
<td>8.</td>
<td>Time-Distance Diagram for Seismic Line 14: Depiction of a Two-Layer Stratigraphy and a Low-Velocity Discontinuity</td>
</tr>
<tr>
<td>9.</td>
<td>Time-Distance Diagram for Seismic Line 19: Depiction of a Two-Layer Stratigraphy and a Low-Velocity Discontinuity</td>
</tr>
<tr>
<td>10.</td>
<td>Frequency and Distribution of Seismic Velocities of the Materials Located in the Bridger and Deer Park Groundwater Discharge Areas</td>
</tr>
<tr>
<td>11.</td>
<td>Examples of Texture of Two Separate Undifferentiated Tills</td>
</tr>
<tr>
<td>12.</td>
<td>Outwash (Left) and Buried Deposits (Right) at a Springhead</td>
</tr>
<tr>
<td>13.</td>
<td>Stream Hydrograph for Maynard Creek</td>
</tr>
<tr>
<td>14.</td>
<td>Location of Sites, Facilities, and Measurement Points</td>
</tr>
<tr>
<td>Figure</td>
<td>Description</td>
</tr>
<tr>
<td>--------</td>
<td>------------------------------------------------------------------------------</td>
</tr>
<tr>
<td>16.</td>
<td>Snow-Water Equivalent of Snowpack: Bridger Bowl SNOTEL Station, Water Years</td>
</tr>
<tr>
<td></td>
<td>1990 and 1991 Compared to 30-Year average (1961-1990)</td>
</tr>
<tr>
<td>17.</td>
<td>Mean Daily Air Temperature Measured at the United States Weather Bureau</td>
</tr>
<tr>
<td></td>
<td>12 NE Station, Maynard Creek Catchment</td>
</tr>
<tr>
<td>18.</td>
<td>Stream Discharge (l/s) for the North and South Forks of Maynard Creek</td>
</tr>
<tr>
<td>19.</td>
<td>The Discharge Class Distribution of Springs at Three Different Times of</td>
</tr>
<tr>
<td></td>
<td>Observation</td>
</tr>
<tr>
<td>20.</td>
<td>Deer Park Spring Hydrograph (Spring 23)</td>
</tr>
<tr>
<td>21.</td>
<td>Deer Park Spring Temperature Variability, April 20, 1991 Through June 7,</td>
</tr>
<tr>
<td></td>
<td>1992</td>
</tr>
<tr>
<td>22.</td>
<td>Temperature Variability of Springs Located at Similar Elevations</td>
</tr>
<tr>
<td>23.</td>
<td>Three Different Spring Water Temperature Regimes</td>
</tr>
<tr>
<td>24.</td>
<td>The Frequency of Springs in Each Morphologic Category</td>
</tr>
<tr>
<td>25.</td>
<td>Flow Duration Curve for Maynard Spring Stream Discharge</td>
</tr>
<tr>
<td>26.</td>
<td>Correlation of All Spring Water Temperatures and Elevation</td>
</tr>
<tr>
<td>27.</td>
<td>Correlation of Spring Water Temperature and Elevation</td>
</tr>
<tr>
<td>28.</td>
<td>The Mean Daily Air Temperature at the Bozeman 12 NE Station and Spring</td>
</tr>
<tr>
<td></td>
<td>Water Temperature of the Deer Park Spring (Spring 23)</td>
</tr>
<tr>
<td>29.</td>
<td>Snow-Water Equivalent at the Maynard Creek SNOTEL Station and Discharge</td>
</tr>
<tr>
<td></td>
<td>from the Deer Park Spring (Spring 23)</td>
</tr>
<tr>
<td>30.</td>
<td>Temperature and Discharge of the Deer Park Spring (Spring 23)</td>
</tr>
<tr>
<td>Figure</td>
<td>Description</td>
</tr>
<tr>
<td>--------</td>
<td>-------------</td>
</tr>
<tr>
<td>31.</td>
<td>Piper Diagram of the Chemical Composition of Select Waters</td>
</tr>
<tr>
<td>32.</td>
<td>Temperature Regimes of Springs Sustained by Bedrock Aquifer Storage (Springs 51 and 53) and Surficial Quaternary Aquifer Storage (Springs 23, 48, and 49)</td>
</tr>
<tr>
<td>33.</td>
<td>Soil Water Discharge Model</td>
</tr>
<tr>
<td>34.</td>
<td>Rock Glacier Aquifer Configuration</td>
</tr>
<tr>
<td>35.</td>
<td>Glacial Outwash and Undifferentiated Till Aquifer Model</td>
</tr>
<tr>
<td>36.</td>
<td>Undifferentiated Till Aquifer Model</td>
</tr>
<tr>
<td>37.</td>
<td>Schematic Interpretation of Seismic Line 14</td>
</tr>
<tr>
<td>38.</td>
<td>Schematic Interpretation of Seismic Line 17</td>
</tr>
<tr>
<td>39.</td>
<td>The Extent and Approximate Thickness of the Deer Park Aquifer</td>
</tr>
<tr>
<td>40.</td>
<td>Cross-Section of the Deer Park Aquifer Including Approximate Values of Storativity (S) in Percent, Hydraulic Conductivity (K) in m/d, and Baseflow Discharge (Qb) in lps</td>
</tr>
<tr>
<td>41.</td>
<td>Response Delay in Spring Discharge to Recharge in Glacial Soils</td>
</tr>
<tr>
<td>42.</td>
<td>Schematic Interpretation of Seismic Line 19</td>
</tr>
<tr>
<td>43.</td>
<td>Schematic Interpretation of Seismic Line 3</td>
</tr>
<tr>
<td>44.</td>
<td>Schematic Interpretation of Seismic Line 4</td>
</tr>
</tbody>
</table>
### LIST OF PLATES

<table>
<thead>
<tr>
<th>Plate</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Geologic Map</td>
<td>insert, back page</td>
</tr>
<tr>
<td>2. Surficial Geologic Map</td>
<td>insert, back page</td>
</tr>
<tr>
<td>3. Surface Hydrology Map</td>
<td>insert, back page</td>
</tr>
</tbody>
</table>
ABSTRACT

The groundwater regime within the Maynard Creek catchment is poorly defined. Aquifers may exist in fractured bedrock and surficial, unconsolidated Quaternary deposits. Ski area and residential development within the catchment has increased water demands. This investigation addresses the following questions: 1) Do the surficial, unconsolidated Quaternary deposits function as aquifers?; 2) Can surficial aquifer discharge be distinguished from bedrock aquifer discharge?; and 3) Can the surficial aquifers be characterized? The techniques used in this investigation include: 1) geologic mapping; 2) stream hydrograph and flow duration curve analyses; 3) groundwater discharge monitoring; 4) hydrogeochemical analyses; 5) material sampling; and 6) seismic refraction.

Geologic mapping was completed to delineate potential aquifers. Groundwater discharge features, including 62 springs, are strongly clustered within surficial deposits. Most springs and seeps, and all perennial streamflow exist at lower elevations where surficial deposits are thickest. Stream hydrograph analyses indicate that discharge is sustained by direct surface water runoff and that groundwater discharge is limited.

Springs within surficial deposits display rapidly increased yields after intense precipitation and snowmelt runoff. Three perennial springs exist and each discharges from surficial deposits. These springs yield between 3 lps (0.1 cfs) and 28 lps (1.0 cfs).

Spring water temperatures decrease with increased elevation by 1.0°C (1.8°F) per 100 m (328 ft). Groundwater discharges from surficial deposits have low winter temperatures (2 to 4°C, 36 to 39°F) that steadily increase through the summer. The average temperature variability of the most persistent surficial springs is 1.9°C (3.4°F). Water temperatures of bedrock springs are higher (5.0°C, 41°F), with an average variability of 0.2°C (0.4°F). Water temperatures of discharge from surficial deposits are rapidly depressed 0.1 to 1.0°C (0.2 to 1.8°F) by meteorological and snowmelt runoff events. The most productive perennial spring's annual water temperature cycle mimics the annual mean daily air temperature cycle with a lag time of 60 days.

Specific electrical conductance of all 62 spring waters was 0.16 to 0.50 (mS). This indicates low ionic concentrations of total dissolved solids and short residence times for stored groundwater. Springs flowing from surficial deposits discharge Ca (calcium) and HCO₃ (bicarbonate) enriched waters. Well waters derived from bedrock are Na (sodium) and HCO₃ (bicarbonate) enriched.

Material sampling and seismic refraction indicate that rock glacier till, undifferentiated till, outwash, and buried channels are the primary components of surficial aquifers. Porosity, storativity, and hydraulic conductivity were approximated for Quaternary materials. Rock glacier till, outwash, and buried channels yield rapid and intermittent groundwater discharge. Undifferentiated tills sustain perennial stream baseflows. The surficial Quaternary aquifers have development potential, but excessive winter withdrawals will reduce perennial stream baseflows.
INTRODUCTION

Groundwater storage and availability in steep mountainous terrain is highly variable and often limited by geologic constraints. In southwestern Montana, groundwater development in Upper Cretaceous rocks often produces low yields and poor water quality, while several Mississippian through Lower Cretaceous formations provide excellent groundwater quantity and quality (Miller, 1974, Moore, 1984, Ferreira and others, 1986). Overlying Quaternary deposits also may function as aquifers, but often they are clayey and do not transmit useful amounts of water, or lack sufficient storage volume to fulfill even modest human needs. In most cases, inadequate data exists for the hydrogeologic regime of mountain aquifer systems to be fully understood.

In the Maynard Creek catchment, on the eastern flank of the Bridger Range (Figure 1), steeply dipping Paleozoic through Upper Cretaceous bedrock is overlain by an undetermined thickness of unconsolidated Quaternary materials. Summer observations reveal an abundance of springs and seeps, and vigorous stream flow. During winter, few springs flow and stream discharge is minimal. The nature of groundwater occurrence in the catchment is unknown.

Resort development plans and increasing recreational activities in and around the Maynard Creek catchment have resulted in demands for additional consumptive and nonconsumptive water uses. Surface water availability from Maynard Creek is severely limited. Surface water is overappropriated and typical summer discharge is less than existing claimed water rights (Morrison-Maierle, Inc., 1978). Groundwater may be a viable resource to supplement the current and future water demands.
Figure 1. Location of the Bridger Range and the Maynard Creek catchment.
The problem of groundwater development in the catchment is that potential bedrock
and surficial Quaternary aquifers have not been identified, and the capacity for water
production from these materials is unknown. The purpose of this investigation is to
determine the significance of surficial Quaternary aquifers. The objectives are to identify
surficial, unconsolidated Quaternary aquifers; to distinguish surficial, unconsolidated
Quaternary aquifer waters from bedrock aquifer waters; and to characterize the components
of the surficial, unconsolidated Quaternary aquifer system in the Maynard Creek catchment.

Geographic Setting

The Maynard Creek catchment is on the eastern flank of the central Bridger Range,
approximately 26 km (16 mi) northeast of Bozeman, Montana (Figure 2). Maynard Creek
flows into Bridger Creek, which is a main tributary of the East Gallatin River. The
catchment is east facing and has 883 m (2897 ft) of local relief, rising from 1774 m (5820
ft) at Bridger Creek to 2657 m (8717 ft) on the crest of the Bridger Range. A total of 5.6
km$^2$ (2.2 mi$^2$) are contained within the catchment boundaries (Figure 2).

Structural Geology

The structural geology of the Bridger Range has been described by McMannis (1955)
and Lageson (1989). The Range is a small north-trending uplift which is approximately 40
km (25 mi) in length. It is located about 80 km (50 mi) east of the Boulder batholith, and
constitutes a part of the Northern Rocky Mountain Front. The Bridger Range is unique in
that it overlaps the boundaries of four major tectonic provinces. These tectonic provinces
are: 1) the Middle Proterozoic Belt Basin; 2) the Sevier fold and thrust belt; 3) the Laramide
foreland province of basement involved deformation; and 4) the Basin and Range province
Figure 2. Topographic map of the Maynard Creek catchment. Taken from the U.S.G.S. 7.5 minute series Saddle Peak Quadrangle, 1987, Provisional Edition.
of present crustal extension (Lageson, 1989). As a result, the Bridger Range contains a stratigraphic and structural record of most of the major tectonic events that have occurred in the Northern Rocky Mountains over the last 1.4 billion years. The Maynard Creek catchment is incised into a discontinuous sequence of overturned Paleozoic through Upper Cretaceous sedimentary rocks that form the eastern limb of a recumbent anticline. The western limb of the Bridger Range anticline is the down-dropped block of a high-angle, normal, extensional fault that forms the Gallatin Valley (Lageson, 1989).

The Bridger Range contains numerous examples of reactivated faults, folded thrust sheets, and overlapping structural families that result from having many different styles of deformation superimposed at one locality (Lageson, 1989). Several of these deformational features exist in the Maynard Creek catchment and influence groundwater recharge, storage, and discharge.

The steeply dipping and overturned stratigraphic section formed by the recumbent east limb of the Bridger Range anticline has profound influence on the groundwater system. The steeply west dipping hydrostratigraphic units have limited area of exposure for aquifer recharge. These "strip aquifers" tend to promote deep circulation of groundwaters, and aquifer recharge is likely transported out of the Maynard Creek catchment (Montagne, 1978; Dunn, 1983).

Faulting within the study area is hydrologically significant. Tectonic deformation during the Proterozoic initiated the Pass Fault, a normal fault that bisects the catchment (Craiglow, 1986). Reactivation of the fault occurred during the Paleozoic, Late-Paleocene, and Early-Eocene (Lageson, 1989). At Maynard Creek, the Pass Fault displays oblique slip movement that resulted in right lateral displacement within the stratigraphic section. The fault is contained between the Pennsylvanian Quadrant formation and the Lower-Cretaceous Kootenai formation. The fault was subsequently intruded by a porphyritic, olivine-augite-biotite diorite dike (McMannis, 1955).
Smaller faults, fractures, and joints occur locally and may affect the development of bedrock aquifers. Parasitic faults have resulted from compressional stresses exerted during cross-range faulting. Conjugate shear, radial, and orthogonal fractures exist within the folded bedrock terrain.

The nonresistant bedrock units in the section are deeply weathered and generally have very low primary porosity. Fracturing increases secondary porosity and the capacity to store and transmit groundwater. The silty and shaley units underlie much of the catchment area, separate potential bedrock aquifers, and form a lower boundary for overlying Quaternary deposits.

**Stratigraphy**

A generalized stratigraphic section for the Maynard Creek catchment has been compiled from the works of previous investigators (Figure 3). The primary porosity of each unit is dependent on lithology, and the units often vary in composition laterally and vertically (Roberts, 1963). The aquifer potential of any unit is greatest where fracturing occurs and secondary porosities are increased. In general, the steeply dipping section may function as a regional recharge area, with the possibility of local groundwater discharge in the Maynard Creek catchment. A detailed stratigraphic description based on field observations by McMannis (1955), Skipp and McGrew (1977), and this author is located in Appendix 1.

**Hydrogeologic Setting**

The groundwater regime within the Maynard Creek catchment has two potential aquifer components; bedrock aquifers and surficial Quaternary aquifers. Potential bedrock aquifers are steeply dipping, resistant, and fractured sedimentary units which are
Figure 3. Generalized stratigraphic section of strata mapped in the Maynard Creek catchment (after McMannis, 1955).
sandwiched between less-resistant, less-permeable, and less-porous shaly units. Dunn (1983), using mathematical simulations of well-test data (taken elsewhere in Bridger Canyon) and probability theory, concluded that the basal sandstone members of the Upper Cretaceous Livingston Group in the catchment would yield as much as 6.8 lps (107 gpm) from two wells with a total drilling depth no greater than 216 m (710 ft). Montagnes' assessment (1978) of groundwater availability from bedrock aquifers within the catchment is less optimistic:

*The steeply inclined structural configuration of the Livingston Group and older formations along the eastern side of the Bridger Range does not seem like a promising arrangement for the production of more than a slight amount of (ground) water... Water would tend to follow layers downward, but this would be of little value because drilling would not be an effective means of obtaining such downward moving water.*

Most groundwater wells in Bridger Canyon are developed in Cretaceous and Tertiary sedimentary rocks where yields and quality are highly variable (Moore, 1984).

The second potential aquifer type consists of surficial, unconsolidated Quaternary deposits. Schrunk (1976) mapped Quaternary geomorphologic deposits for part of the Bridger Range, but did not map the Maynard Creek area. A previous investigation of debris flows in the lower catchment has shown that localized channeling exists in the heterogeneous and anisotropic, unconsolidated materials. These localized zones of higher hydraulic conductivity exist within materials that display low overall hydraulic conductivity (Schafer and Assoc., 1990). Montagne (1978) describes the general hydrogeologic significance of surficial materials in the catchment:

*Chaotic mixtures of large to small boulders encased in finer materials such as silt and clay, ... were eroded from the local mountain flank and transported downhill by landslides, glaciers, and streams. The estimated thickness of this veneer is from 100 feet to less than 25 feet. Because clay content is mostly high, water does not pass easily through most of this deposit, but in places such as the thresholds of the upper bowls ... water passes into the veneer as in an open sieve. The springs which emanate from the veneer at various places in the Bridger Bowl area are mostly sustained during Spring, Summer, Fall and part of Winter by this storage system and should be considered important mechanisms in maintaining the surface flows of Maynard Creek and its associated streams.*
Well and spring development in the surficial unconsolidated materials is uncommon and poorly documented. Unconsolidated deposits in the catchment are likely to store infiltrating waters, but the character and quantity of the stored water is unknown. The most productive springs in the catchment have been developed, but the source of the groundwater has not been determined. Previous work has shown that surficial unconsolidated materials similar to those found in the Maynard Creek catchment do function as aquifers and sustain spring discharge (Valdiya and Bartarya, 1991).

**Hydrologic Setting**

The Maynard Creek catchment contains a third-order stream network which has a palmate dendritic shape. The drainage density of the entire catchment, calculated by using stream lengths portrayed on a 7.5 minute topographic map, is approximately 1.8 km/km² (2.9 mi/mi²)(Lee, 1980). The steep and entrenched, bedrock, boulder, and cobble bedded stream system flows vigorously during snowmelt and rainstorm generated runoff events. During low flow periods, the stream network is less extensive. Common Rosgen (1994) stream channel types are A1, A2, A3, A4, B2, B3, and B4. The channel network includes ephemeral, intermittent, and perennial reaches.

The average annual precipitation for the entire catchment ranges between 47 cm (18 in) and 127 cm (50 in), with an average annual snowfall between 254 cm (100 in) and 1016 cm (400 in) (Morrison-Maierle, Inc., 1978). The "melting-from-above" of late season snow patches produces subnival stream flow that maintains sediment transport in the upper ephemeral reaches of the stream channel network (Gardner, 1986). Stream flow during late summer is limited to short reaches of the north and south forks that are located below perennial springs. A few observations of stream discharge have been recorded during winter baseflow conditions (Williams, 1967).
The waters of Maynard Creek are used to fulfill a variety of human needs. Irrigation and stock watering have traditionally been the primary uses of Maynard Creek waters. Bridger Creek and its tributaries (including Maynard Creek) total maximum yield during the irrigation season ranges from 2.5% to 40% of the claimed water rights on Bridger Creek (Morrison-Maierle, Inc., 1978). A storage pond exists on the main stem of Maynard Creek below Bridger Bowl Ski Area.

The Problem

Sustaining human activities in high mountain environments requires consumptive use of water. When surface waters are unavailable, users must explore the groundwater development potential. Groundwater development may be a means to supplement water demands incurred by recreational activities and resort expansion in and around the Maynard Creek catchment. The groundwater regime has two probable aquifer components; bedrock aquifers and surficial, unconsolidated Quaternary aquifers. The problem is the significance of each aquifer type is unknown.

Purpose

This investigation will determine the function of surficial, unconsolidated Quaternary deposits as components of the groundwater regime in the Maynard Creek catchment. The investigation will address the following questions:

1. Do the surficial, unconsolidated Quaternary deposits function as aquifers?
2. Can groundwaters stored in and discharged from surficial Quaternary aquifers be distinguished from groundwaters derived from bedrock aquifers?
3. If surficial, unconsolidated Quaternary deposits are aquifers, can these aquifers be characterized?
11

METHODS

Groundwater investigations in rugged mountain environments are often restricted by a lack of information and the difficulty of acquiring data from ground-based methods. Other factors that hamper the study of mountain groundwater systems include the propensity for deep groundwater circulation and the variable position and configuration of the water table that is often independent of surface topography (Domenico and Schwartz, 1990). In many cases, the most effective strategy to describe and interpret alpine aquifer systems is to characterize geologic components of the system, and map and monitor the surface features of the groundwater regime (Meyboom, 1966a). This investigation employs conventional geologic and geographic mapping procedures, a geophysical exploration technique, and hydrogeologic and hydrologic methods.

Mapping

Aerial Photographs and Existing Maps

Black-and-white stereo photo pairs from 1981 and 1988, color stereo-pairs from 1984, and large scale (1:12000) black-and-white and color infrared (IR) photographs were used for this investigation. All field mapping was conducted with the aide of available imagery. A Bausch & Lomb 10x stereoscope was used to complete mapping and editing in the office.
The United States Geological Survey (U.S.G.S.) Saddle Peak, Montana, 7.5 Minute Series Quadrangle (1987 provisional edition) was used as a base map for this investigation. An engineering map (1:2500) of the lower elevations of the Maynard Creek area also was used for site investigations (Morrison-Maierle, Inc., 1990). The maps were used to record spatial data, to identify geologic and hydrogeologic features, and to construct a digitized base map and database with Arc/Info Workstation Version 6.1 software.

Field information was recorded on enlargements of the 1987 Saddle Peak 7.5 Minute Series Quadrangle map. The topographic map was enlarged to a scale of 1:8000 to enable detailed field mapping. Field data was transferred from the enlargements onto mylar film and then digitized for applications of Arc/Info. All thematic base maps are 1:8000 scale and constructed by overlaying digitized field data coverages onto the digitized reproduction of part of the Saddle Peak Quadrangle.

Geologic Mapping

A geologic map of the Maynard Creek catchment was completed to define the location of all units and their contacts, and to identify potential bedrock aquifers within the study area. Fault mapping was completed with aerial photographs and field inspection. Fracture trace mapping includes all traces in bedrock that have an apparent length greater than approximately 300 m (984 ft) and are evident on aerial photographs and topographic maps (Sabins, 1978). The bedrock geology map was completed using conventional techniques described by Billings (1972), McClay (1987), Butler and Bell (1988), and Hatcher (1990). Field instruments included Silva and Brunton compasses and a Thommen 15000 altimeter. Numerous traverses of the field area were made perpendicular to the strike of bedrock units to maximize the number of observed contacts. Additional information was collected where repeated sections, faulting, and extensive fracturing were located.
Geomorphologic Mapping

The geomorphology of the Maynard Creek catchment has received little attention from previous workers. Schrunk (1976) mapped the surficial geology of the northeastern Bridger Range, but did not include the Maynard Creek area. Skipp and McMannis (1971) mapped the surficial materials that cover the central Maynard Creek area as one continuous Quaternary landslide deposit, with older alluvium found at the distal end of the catchment. Schafer and Associates (1990) describe one large landform within the catchment as mass wasting debris. McMannis (1955) speculated that alpine glaciation did not occur in this portion of the Bridger Range. This point is disputed by Montagne (1978) and Locke and others (1985), who described glacial processes in the study area.

The geomorphology of the Maynard Creek catchment was mapped, at a scale of 1:8000, after three criteria were established. First, material type and genesis were included in the descriptions of all surficial map units. Second, distinct geomorphologic materials were considered as unique hydrostratigraphic materials. Third, field criteria were devised to define gradational contacts between bedrock and surficial unconsolidated deposits.

The strategies, guidelines, symbolisms, and special techniques used during geomorphologic mapping are described by Varnes (1978), Selby (1982), Dackombe and Gardiner (1983), McCalpin (1984), De Graaff and others (1987), Rupke and others (1988), and Cooke and Doornkamp (1990). Geomorphologic mapping was conducted after completion of the bedrock map. All bedrock-surficial contacts were traced laterally and mapped by inspection. Bedrock contacts with surficial deposits were defined where surficial materials were inferred to be less than 0.5 m (1.7 ft) thick. This thickness exists where bedrock or regolith could be located by hand-digging.

Where two or more unique Quaternary deposits are superimposed, only the uppermost one is depicted. Contacts between distinct surficial materials were defined by morphologic and/or lithologic differences observed in the field. Thus, the investigator
recognized surficial unconsolidated materials as mappable and unique if they were: 1) distinguishable on aerial photographs; 2) noted during field observation as having identifiably unique morphologic characteristics; or 3) composed of noticeably different materials. Mass wasting was classified with a system described by Varnes (1978).

Hydrogeologic Mapping

Groundwater discharge at the surface may be expressed as springs, seeps, saline soils, perennial and intermittent streams, ponds, or bogs. Understanding these surface features requires some knowledge of the nature of groundwater discharge zones (Meyboom, 1966a). The hydrogeologic maps completed for the Maynard Creek catchment record stream, spring, seep, standing water, and sag pond locations. The spatial distribution of these surface features of groundwater discharge are used to identify shallow aquifer systems in the Maynard Creek area.

Location of surface features of groundwater out-flow was the first step in hydrogeologic mapping. A color IR photograph (1:12000) was used to locate dense phreatophytic vegetation. This vegetation often is associated with high water tables and groundwater discharge zones (Meinzer, 1927; Meyboom, 1966b). Secondly, a systematic "saturation" search method (May, 1973), where all of the terrain is inspected manually, was used to locate additional discharge features in the catchment. Descriptive and quantitative data was collected at each site.

Field mapping criteria were established to ensure consistent and concise data collection. Surface hydrogeologic features were categorized, and specific measurements were taken at each observation site. A regular schedule of observation during the spring, summer, and autumn of 1990 and 1991 was followed to record the spatial and temporal variability of discharge features within the Maynard Creek study area.
Aquifer Material Characterization

After mapping the Maynard Creek catchment, it became apparent that many of the streams, springs, and seeps were related to groundwater storage in and movement through Quaternary deposits. The most probable surficial aquifers were identified and selected for further detailed investigation. Published values for hydrogeologic parameters of materials similar to those in the study area were assembled. Seismic refraction was used to approximate surficial deposit thicknesses, to estimate seismic velocities of several geologic materials, and to profile bedrock surfaces that underlie Quaternary overburden. In addition, site examination was completed using mechanical drilling, soil pits, and percolation tests, and during development of a spring in the study area.

Surficial Materials and Potential Aquifers

Surficial materials in alpine catchments often intermix and their contacts may be indistinct (De Graaff and others, 1987; Rupke and others, 1988). Geomorphologic contacts have been mapped as gradational, and potential aquifers may consist of more than one type of material. There are many locations in the catchment where surficial unconsolidated materials may form aquifers.

The potential, surficial unconsolidated aquifers can be recognized by several common characteristics. Often they are isolated and may consist of thick overburden deposits located between hydrologic divides where unconfined groundwater flow is convergent. They can occur where thick and porous materials overlie impermeable bedrock. These potential aquifers also contain or lie immediately up-gradient from the most prominent spring lines, spring clusters, and/or seeps.
Existing Research

Existing literature was used to provide estimated ranges of values for hydrogeologic properties of materials similar to those found in the Maynard Creek catchment. Values for porosity, storativity, and hydraulic conductivity were taken from the results of previous investigations. These values will be used with other results to characterize surficial Quaternary aquifers in the study area.

Seismic Refraction

Seismic refraction techniques are useful for investigations of thin hillslope deposits (Kesel, 1976; Olson and Doolittle, 1985; Locke, 1987; Mills, 1990; McCann and Forster 1990). For this investigation, the thicknesses and seismic velocities of Quaternary deposits, the existence of covered bedrock units, and the shapes of buried bedrock surfaces have been interpreted with seismic refraction methods. Time-distance plots and the distance-delay method were used to calculate seismic velocities and overburden thicknesses of consolidated and unconsolidated materials (Redpath, 1973; Dobrin, 1976; Haeni, 1988). In addition, the calculated seismic velocities of materials in this study were compared to velocities determined during previous investigations of similar materials (Faust, 1951; Wollard and Hansen, 1954; Press, 1966; Redpath, 1973; Locke, 1987; Mills, 1990).

An EG&G Geometries 12-channel signal enhanced seismograph was used for this investigation. A 5.45 kg (12 lb) sledge hammer served as the energy source. Mark Products 100 MHz geophones were used for their high sensitivity to seismic energy.

The seismic refraction survey was conducted on two isolated, potential surficial aquifers during October 1990. Seismic velocities of exposed shale, undifferentiated till, and man-made fill were determined first. Later, refraction measurements were taken along linear transects that lie upslope of and contour around the most productive perennial springs. Seismic lines were placed parallel or near-parallel to contours. Most line lengths
were 65 m (213 ft), except where thick vegetation and steep slopes were encountered. The seismic spread length was approximated by the critical-distance method (Redpath, 1973). This line length allowed recognition of first layer thicknesses of 5 m (16 ft) to 20 m (66 ft), depending on velocity contrasts between the two upper layers. Geophone spacing was fixed at 5.0 m (16.4 ft) to standardize measurements, maximize areal coverage, and maintain a high level of resolution of small subsurface features. A forward and reverse velocity-distance profile was completed for each seismic line. Multiple hammer strikes were used at each line to enable greater line length and better resolution of first arrivals. Signal enhancement was used to identify the timing of first wave arrivals at each geophone.

Site Examination

Specific sites were examined within potential surficial Quaternary aquifer deposits. Cluster sampling along a linear transect was completed with a truck-mounted Giddings' hydraulic soil sampler. Core and auger samples were described, and depths to a saturated zone were noted.

Soil pits were dug to expose specific surficial materials. The physical characteristics of soil profiles were described, especially where high primary and secondary porosities were noted. Falling head percolation tests were used to estimate the rate of unsaturated flow in sampled materials. The tests were completed at two sites to fulfill Park County Health Department Subsurface Sewage Treatment System requirements for the design of a soil absorption field on sloping ground.

Several springs within the catchment have been developed for domestic use. At one location a spring was developed by this investigator for residential use. The physical characteristics of the site and materials were visually observed. Three samples were collected directly from aquifer material during excavation of the spring site. These
materials were used to make an ocular description of the size and shape of surficial materials directly associated with groundwater discharge.

Hydrology

Existing Data

Existing hydrologic and meteorologic information is available to assist in the interpretation of aquifer types and characteristics. This information includes estimations of monthly stream yields (Morrison-Maierle, Inc., 1978) and stream discharge data collected by Williams (1967). Also, long-term meteorological records of temperature, precipitation, and snow cover have been maintained at the United States Weather Bureau Bozeman 12 NE Station. The station is located on the eastern boundary of the Maynard Creek catchment. In addition, continuous records of snow-water equivalent are maintained at two Natural Resources and Conservation Service SNOTEL stations. The 30-year average snow-water equivalence also was used for this interpretation. The uppermost station is referred to as the Bridger Bowl station, while the lower one is called the Maynard Creek station.

Stream Discharge Measurements

Stream discharge measurements were taken on two uppermost perennial stream reaches of the north and south forks of Maynard Creek during the low flow period. Stream stage was very low and discharge was measured by the float method (U.S. Department of Interior, 1985a). Stream velocity was approximated as 0.85 of the surface float velocity in the thalweg.
Water Chemistry

Existing Data

Major ion concentrations in groundwater have been used by other researchers to determine the origin of groundwater in mountain environments (Fritz and others, 1990; Margaritz and others, 1990). Chemistry data for stream waters, groundwaters derived from wells, and springs in the Maynard Creek catchment is available (Morrison-Maierle, Inc., 1978; Montana Department of Health and Environmental Sciences, Water Quality Bureau, 1984, 1987, 1990; Chen-Northern, Inc., 1991).

Field and Laboratory Methods

Two springs in the catchment were sampled in early March during the historical low flow period (Morrison-Maierle, Inc., 1978) when mixing of through flow waters is low (Martinec and others, 1982; Hem, 1989). Samples were collected using standard methods (Brown, Skougstad, and Fishman, 1970; Lloyd and Heathcote, 1985). The spring water samples were filtered, acidified, and stored on ice. The samples were delivered to the Soil Analytical Lab at Montana State University for immediate processing within two hours after collection. An argon plasma process was used for spectrographic analysis of the elemental concentrations in spring waters.

For this investigation, two spring water samples were analyzed for calcium (Ca), magnesium (Mg), potassium (K), sodium (Na), iron (Fe), chlorine (Cl), bicarbonate (HCO₃⁻), sulfate (SO₄²⁻), specific electrical conductance (SC), and pH. Water temperature was measured in the field. Historical water chemistry analyses of waters sampled were compared to the chemical analyses completed during for this investigation. The data was tabulated and plotted on a Piper diagram (Piper, 1944, Hem, 1989).
Spring Water Monitoring

Many spring water characteristics can be easily measured and monitored in the field. These characteristics have been used in other investigations to define the areal extent and nature of aquifer systems that discharge at springs (Magaritz and others, 1990; Fritz and others, 1990). Also, seasonal fluctuations in spring water qualities have been used to determine aquifer characteristics that control the timing and periodicity of groundwater discharge in mountainous environments (Kattlemann, 1989; Blanchard and others, 1991). The spatial and temporal nature of groundwater discharge has been recorded as a means of describing the groundwater regime in the Maynard Creek catchment.

A definition of a "spring" was established to distinguish different forms of groundwater discharge points in the field area. In this investigation, a spring is mappable if it fulfills three criteria. First, the volume of spring discharge must be sufficient to float a small stick and exceed approximately 0.06 lps (1 gpm). Repeated observations of 0.06 lps (1 gpm) channelized flow were made under controlled conditions to develop a recognition of 0.06 lps (1 gpm) flow in the field. Secondly, spring discharge must flow from a discrete point or set of points and not as a broad area of diffuse discharge (seeps). Finally, discharge points separated by 3 m (9.9 ft) or more were considered unique springs.

Spring Inventory and Monitoring

The unique morphology and character of a spring is often related to the process that causes spring occurrence at a given location (Bryan, 1919; Taylor, 1969). All spring locations were marked with a bamboo pole, flagging tape, or some natural object. Springhead morphologies were recorded. Also, landscape features were inspected for indications of spring water origins.
At a few locations separate springs were thought to be physically connected. The associated springs exist along a linear feature or discharge disappears to emerge down-gradient to form another discharge point. These physically associated springs have been referred to as spring lines and emergent springs (Bryan, 1919; Meinzer, 1927). If the springheads outcrop at distances greater than 3 m (9.9 ft) and are thought to be connected, a note of this apparent association was recorded.

All springs were then visited on a biweekly basis, and records were kept for each visit. Monitoring during the spring, summer, and autumn of 1990 consisted of observations of spring locations, changes of locations, and seasonal flow duration. Monitoring between May and October 1991 included measurements of discharges, temperatures, specific electrical conductances, and descriptions of changes in spring morphologies. Migration of discharge points was noted. Several perennial springs were monitored more frequently during the months of April, May, and June to record spring response to rapid snow-melt conditions.

**Spring Discharge**

All spring discharge volumes were placed in one of three discharge classes; 1) >0.06 lps (1 gpm) and <0.32 lps (5 gpm); 2) 0.32 lps (5 gpm) to 1.26 lps (20 gpm); or 3) >1.26 lps (>20 gpm). Spring flow was measured at many locations, especially where questionable intermediate discharge volumes occurred. Ocular approximation was used to distinguish obvious high and low discharge springs. The use of ocular methods instead of actual measurements allowed all spring observations to be completed in a single twenty-four hour period. This reduced the potential of greater temporal variability of measurements recorded over a longer time period.

Several techniques were used to measure spring discharge volumes. Developed springs had overflow pipes that were positioned above ground to facilitate measurement.
The Deer Park spring, located at an elevation of 2006 m (6580 ft) near the south fork of Maynard Creek, was measured with a 19 l (5 gal) bucket and stopwatch. Measurements were repeated three times at each discharge point to determine the average spring discharge.

Discharge also was measured with a portable weir formed from sheet metal and drained by 6 m (20 ft) of 6 cm (1.5 in) internal diameter flexible hose. The weir was placed below intermediate discharge springs, perpendicular to flow, with the hose running downstream. Flow volumes near 0.32 lps (5 gpm) were measured with a stopwatch and one 0.95 l (1 qt) bottle, while springs that discharged approximately 1.26 lps (20 gpm) were measured with a 3.8 l (1 gal) jug.

**Specific Electrical Conductance**

Specific electrical conductance readings were taken with a Cole-Parmer 4070 conductivity meter. The instrument was calibrated by the Soil Analytical Lab at Montana State University. Instrument readings were taken after the probe had been thoroughly rinsed and immersed for approximately two minutes, and were repeated until reproducible values were achieved. Specific electrical conductance units are millisiemens (mS), and readings were automatically adjusted by the instrument to standard values at 25°C (77°F).

**Spring Water Temperature**

All spring water temperatures were measured during the 1991 field season. Measurements were taken with a VWR 500 Scientific Digital Thermometer. The instrument was calibrated in iced water, where temperatures are maintained at 0°C (32°F). The measurements were taken at the springhead while the temperature probe was inserted into the springhead as deeply as possible. Temperature readings were taken after two minutes to allow for instrument equilibration.
RESULTS

Mapping

Geologic Mapping

Specific results have been achieved by mapping the geology of the Maynard Creek catchment. They are: 1) identification of potential bedrock aquifer units; 2) identification of hydrologically confining bedrock units; and 3) location of fractures, traces, and faults within the catchment. A geologic map that includes outcrop exposure was prepared for this investigation (Plate I). Large areas of nearly continuous outcrop exposure within Upper Mesozoic strata or younger have been located and mapped as darkened patterns. Ellis Group, Quadrant-Amsden-Big Snowy Group, and Mission Canyon formation outcrops have nearly continuous exposure throughout the catchment, and have not been highlighted on the geologic map. Few outcrops occur in the Colorado Group, or in the Morrison, Kootenai, and Telegraph Creek formations. Outcrops are abundant in the Eagle formation and the Livingston Group.

The most resistant bedrock units in the catchment form prominent north-south trending ridges. All competent sandstone, siltstone, and limestone units are potential aquifers, but they display limited primary porosity and highly variable secondary porosity that is a function of fracturing. Paleozoic and Mesozoic strata located at the upper and middle portions of the catchment contain several known aquifers of regional significance. The ridge-forming Mission Canyon limestone, a member of the Madison Group, is
generally recognized as a major regional aquifer (Miller, 1974; Plummer and others, 1990). In the Maynard Creek catchment, this unit dips steeply and plunges downward for thousands of meters, extending to the sub-Bridger thrust zone (Lageson, 1989).

Many formations that exist in the study area are also recognized as aquifers elsewhere in Montana (Miller, 1974; Thompson and Custer, 1976; Donovan and others, 1981; Dunn, 1983; Moore, 1984; Ferreira and others, 1986). Other potential aquifer units in this study area include the Quadrant quartzite, Eagle sandstone, sandstone members of the Ellis Group, Kootenai formation, Colorado Group, and the Livingston Group. All units have been described by McMannis (1955) and Skipp and McGrew (1977) (Appendix 1, p.115).

The bedrock aquifers dip steeply to the east or west (Plate I). Most potential aquifer units are "sandwiched" between silty or shaley units. The less competent, easily eroded units are difficult to identify in the field, but generally exist between resistant units and form topographic depressions or gentle slopes. These shaly or silty units are known to have very low primary porosities and limited secondary porosities, even where fracturing has occurred (Miller, 1974; Dunn, 1983).

Large differences in hydraulic conductivity occur between members of the same formation. This type of boundary condition between potential bedrock aquifers and less permeable layers creates "strip aquifers" (Dunn, 1983). The strip aquifers in this study area were identified by Dunn, have variable thicknesses of 10 m (33 ft) to 100 m (328 ft), and are thought to be laterally discontinuous. The lateral extent of the strip aquifers is not easily determined due to covered contacts and facies changes within the units.

Fracture traces that extend beyond the catchment boundary have been identified (Plate 1). Significant faults and zones of fault controlled fracturing also have been mapped. Extensive fracturing within individual outcrops was noted.

Fracture traces, ranging from 300 m (990) to 1200 m (3960 ft) in length, are most distinctly visible in bedrock on medium scale, vertical aerial photographs that include
Maynard Creek and its adjacent catchments. The lower catchment (up-section) contains at least five visible linear features that may influence groundwater movement. The southwest to northeast-trending features fit into an *en echelon* pattern with other linear features that exist to the north and west of Maynard Creek, where the entire stratigraphic section bends toward the northwest (Skipp and McMannis, 1971).

Field evidence of the fracture traces includes the predominance of steep, east dipping strata in the southeast quadrant of the catchment and the predominance of steeply southwest dipping strata in the northeast quadrant. In addition, bedding within the central portion of the northeast quadrant displays a trend of having either north or northwest bearing strikes. No slickensides, slickenfibers, shear zones, or measurable displacements were observed in association with these fracture traces.

Other linear features have been located and mapped in the western portion of the catchment. The long, linear ridge crest of the Bridger Range has been segmented at several locations along the catchment's western boundary. At six locations, the continuity of the east and west facing slopes that descend from the ridge crest is disrupted by linear features. Topographic displacement, saddles, and coincident drainages on each side of the range exist where the fracture traces intersect the ridge crest.

The Pass Fault, which terminates in the Maynard Creek catchment, has been mapped and described by previous workers (McMannis, 1955; Skipp and McMannis, 1971; Craiglow, 1986; Lageson, 1989). The fault bisects the northwest quadrant of the catchment and offsets a portion of the section with right-lateral movement and net slip of less than 152 m (500 ft) (McMannis, 1955). High-angle, oblique slip, lateral thrust ramps exist along the fault's transverse zone (Lageson, 1989). Intrusion into the fault zone is thought to have occurred after faulting (McMannis, 1955). The olivine-augite-biotite diorite dike has not experienced tectonic movement following intrusion (McMannis, 1955). Few outcrops of the dike have been located within the catchment, but regolith is found at
many locations. The crumbly, green-brown, clayey regolith is distinct from the surrounding materials and often underlies sites of initiation of mass movement. No open fractures or jointing were observed within the dike.

Other areas of faulting exist within the catchment. A zone of deformation has been identified on the southwestern corner of the catchment near the 2379 m (7802 ft) point known as "Pierre's Knob". Here the Ellis Group strata dip 75°W at the contact with the overlying Morrison formation. The basal Sawtooth member of the Ellis Group contains a chert breccia that lies in a near vertical position in contact with the underlying Quadrant formation. The upper Quadrant member dips 68°E at this contact. The orientation of the ridge forming Mission Canyon limestone was measured as approximately N 20°E and 60°SE near this location. Skipp and McMannis (1971) mapped a fault with apparent left-lateral motion within the Ellis, Quadrant-Amsden-Big Snowy, and Mission Canyon formations approximately 1 km (3300 ft) south of Pierre's Knob. In addition, the axes of four eroded gullies plunge northeastward within the Quadrant-Amsden-Big Snowy strata and intersect steeply dipping Amsden-Big Snowy strata at low angles. The strikes of the outcrops that contain the gullies are different than those of the surrounding outcrops. Also, field observations of preferential erosion suggests deformation at this location, yet no slickensides, fault breccia, measured displacement, or other direct evidence of faulting was located. These fractures are inferred faults.

Another fault is located in the west-central portion of the catchment at 2195 m (7200 ft) where rotational slumping of surficial and bedrock materials uncovered resistant bedrock that displays significant fracturing. Open bedrock fractures exist along the north-south trending trace of the fault. Topographic expression of the faulted area indicates down-dropping of the east wall. The fault surface is covered by unconsolidated materials at its northern end. At this location rolling breaks in slope profile and deep fractures in overburden suggest that deep rock creep has occurred.
A set of three faults is located in the northwestern corner of the catchment between 2440 m (8000 ft) and 2622 m (8600 ft). The vertical displacement of the two southern faults is most apparent on the north facing slope, as seen when looking from the north to the south. In aerial view, the two faults display left-lateral motion, as suggested by Skipp and McMannis (1971). These high-angle, normal, oblique slip, oblique faults fit an apparent en echelon pattern. The southern most fault displays a fault trace that extends hundreds of meters southwest-ward. The northern fault is best seen in aerial stereo photo-pairs, where right-lateral bedding displacement is visible.

The smallest hydrologically significant fracture patterns exist within individual outcrops. The fracturing observed within the Mission Canyon formation is primarily jointing. The most prominent outcrops form east-facing flatirons where the face of the outcrop is a jointed surface. The jointing intersects true bedding at intermediate angles. Joint planes strike north-south, have near vertical dips, and display conjugate sets at several locations. In many cases, the joints lack an east wall because the eastern blocks have detached as large rock fall, and the west wall forms nearly vertical, smooth faces. This is most evident along the upper end of talus cones immediately north of the "South Bowl", at 2378 m (7800 ft), and at the upper perimeter of the "North Bowl" where a prominent gully exists at 2500 m (8200 ft). The joints display systematic and nonsystematic patterns. The Mission Canyon formation contains extensive internal deformation and faulting.

A few nonsystematic fractures have been observed in the Amsden-Big Snowy strata. The silty, dolomitic unit is typically less resistant than other surrounding units, and some of its fractures have been filled with weathered residue. The Quadrant quartzite forms prominent and extensive outcrops that display widely-spaced, bedding-parallel fractures and a few orthogonal fractures. The Ellis Group has good exposure throughout the catchment and displays variable fracture density at all outcrops. The Kootenai formation has few outcrops in the catchment and displays minor bedding-parallel fracturing, except
where faulting occurs. The Colorado group is poorly exposed, with the exception of one outcrop located along the catchment's southern boundary. At this outcrop, closely-spaced, bedding-parallel fractures in competent bedrock are apparent. Continuous, bedding-parallel fractures occur throughout the exposed Eagle sandstone. Extensive systematic and nonsystematic fractures exist in all outcrops of the Livingston Group.

Geomorphologic Mapping

Geomorphologic mapping identified: 1) contacts between surficial materials and bedrock; 2) genetically and/or morphologically unique surficial Quaternary deposits and materials; and 3) isolated surficial hydrogeologic features. The contact between surficial materials and bedrock is portrayed on Plate 2. Contacts also separate surficial materials that have genetically different origins. Contacts have been placed where distinct morphology defines the individual deposits. For example, distinct morphologies define contacts between adjacent talus cones or separate rockfall deposits. In cases where a younger deposit covers unconsolidated material of unknown age or origin, the uppermost material is described and depicted on the surficial geology map.

Unique surficial deposits have been described and mapped (Plate 2). The genetic material types that compose each deposit has been identified. Specific sites have been investigated in detail to help distinguish compositional differences between selected geomorphologic units. Several isolated hydrogeologic features were located within surficial deposits, but were too small to be mapped at 1:8000. The features are drain holes, sapping, and piping, and are discussed in interpretations of specific Quaternary aquifers.

The surficial deposits mapped in the Maynard Creek catchment are divided into four separate categories: 1) glacial; 2) alluvial; 3) colluvial; and 4) mass wasting. Each category has subdivisions. Not all physical characteristics that define sub-categories are completely unique or exclusive.
Glacial deposits cover the greatest amount of surface area in the catchment. The three types of glacial deposits mapped during this investigation are undifferentiated till, glacial outwash, and rock glacier deposits. The undifferentiated tills include subglacial, englacial, and supraglacial deposits of unknown age and proportion. Outwash derived from glacial deposits that lies in contact with the source has been mapped as glacial in origin. The rock glacier displays distinctive morphology and material composition which indicates that glacial processes were involved in the formation of the landform.

The undifferentiated glacial materials are variably thick, heterogeneous and anisotropic, and form much of the landscape in the catchment. These materials do form unique glacial deposits and landforms. In general, the undifferentiated materials are matrix-supported, clay cobble or clay boulder tills. A wide range of compositional variability exists within the till. Several locations display materials that represent the opposite end member of the fabric type continuum; namely clast-supported, sandy clay cobble or sandy clay boulder tills.

Undifferentiated glacial deposits form medial, lateral, and terminal moraines at many locations. Moraines were mapped on the basis of size as either large or small. Large moraines appear to be greater than ten meters thick and are laterally extensive. The map symbol indicates the approximate position of the moraine crest and not the maximum down-slope extent of the moraine toe-slope. In several cases, the use of one continuous moraine symbol represents small and overlapping moraine deposits, or an en echelon moraine deposit. The en echelon arrangement occurs along the northern boundary of the catchment.

Moraines in the catchment are predominantly lateral moraines. Most terminal moraines have been deeply dissected by glacio-fluvial and modern channel-forming processes. Thick, undifferentiated till forms a truncated terminal moraine between 1963 m (6440 ft) and 2000 m (6560 ft). This discontinuous complex of glacial material is deeply
dissected by stream channels, has been altered by other erosional processes, and lacks the distinct morphology of a moraine. The deposit is at least 15 m (50 ft) thick.

At several locations, distinct landform morphology and unique material characteristics suggest the existence of glacial outwash deposits. An example is the area located between 1988 m (6520 ft) and 2037 m (6680 ft) along the south fork of Maynard Creek. At this location, a broad and relatively uniform slope gently descends to its distal end, where distinct abandoned channel levees exist. The slope is composed of poorly to moderately sorted, subangular to subrounded, gravel and cobble clasts that contain subordinate volumes of finer material. The linear and subparallel channel levee deposits are arranged parallel to the dip in slope and contain predominantly large cobble to small boulder clasts. The levees are inactive, well embedded with fine material, and rest approximately 1 m (3.3 ft) to 2 m (6.6 ft) above the modern flood prone area. The entire outwash area occupies the lower toe-slope of a thick moraine-like, undifferentiated glacial deposit (Plate 2).

A second outwash area is located between 1988 m (6520 ft) and 2037 m (6680 ft) along the north fork of Maynard Creek. The broad, low-angle slope displays a distinct fan shape in the field and on a topographic map. Excavation for culvert installation exposed sorted, subrounded to rounded, small cobble clasts and a sand and gravel matrix. The surface of the deposit contains abundant coarse gravels and cobbles. The glacio-fluvial outwash fan lies immediately downslope from a prominent moraine and originates at a point of deep incision where the moraine is breached by a large, active stream channel. Stream discharge from the south fork of the north fork of Maynard Creek was observed to deposit coarse gravels on the upper fan surface. The northern portion of the fan is still actively adjusting to sediment deposition from above and channel development at the toe.

The remaining outwash deposit is located between 1823 m (5980 ft) and 1927 m (6320 ft), and formed by separate processes and events. The southwestern and northern portions of the deposit display distinct morphologies but the area between the deposits has
been greatly altered by ski run construction. The southwestern portion of the deposit displays a fan morphology and is confined between a steep, terminal moraine lee-slope and a steep, bedrock hillside. The lobate slope is littered with small, angular to subangular, heterolithic boulders. The bouldery material can be found as high as 1890 m (6200 ft) on the south embankment of the southern-most branch of Maynard Creek. This branch forms the southern boundary of the deposit between 1860 m (6100 ft) and 1890 m (6200 ft), and has aggraded with subangular to rounded, large cobbles and boulders. A small but deep sub-catchment lies above the deposit, immediately beyond a steep and scoured bedrock channel. The sub-catchment is confined at its lower end where a large moraine contacts an adjacent bedrock ridge. The sub-catchment released periodic flood flows that influenced the development of the southern portion of the outwash complex.

The northern portion of the deposit forms a smooth and gentle slope that descends from the toe-slope of an associated moraine. The surface of this slope is dominated by angular to subrounded gravels, cobbles, and small boulders. A 1 m (3.3 ft) deep trench was dug for the installation of snow-making equipment. The trench runs from the large pond on Maynard Creek to the top of the prominent moraine crest. The materials encountered contained abundant gravels, cobbles, and boulders near the lower end of the trench, but graded imperceptively into matrix-rich materials near the upper end of the trench. Also, the entire area east of the prominent road bend at 1866 m (6120 ft) consists of poorly to moderately sorted, predominantly large cobbles and boulders that are embedded in fine material. This area also contains many abandoned channel levees and other subdued, levee-like features. The outwash deposit was mapped to the farthest eastward extent of the levee deposit that coincided with coarse, sorted materials.

A small rock glacier is located in the northwestern extent of the glacial deposits. The deposit shape is relatively unmodified by weathering processes and appears distinctly younger than the underlying till. In plan view, the feature has the shape of a small glacier.
The ridge that contains the deposit is a moraine. The landform has forest vegetation which suggests that it is relatively stable and not moving at a rate comparable to that of modern active rock glaciers (Giardino and Vick, 1987). Large blocks (< 5 m, 16.5 ft) and boulders create unfilled voids in the chaotic debris. Microrelief forms maze-like depressions and ridges within the continuous bouldery perimeter formed by the moraine. Several conical depressions exist within the labyrinth of internal ridges.

The upper margin of the rock glacier grades into a talus slope. A continuous ridge of angular limestone blocks and boulders form a distinct protalus rampart (Catt, 1988) that rests on the talus-rock glacier transition zone. Accumulation of the large boulder debris is facilitated by late season snowpacks that allow rockfall to slide to a preferred zone of deposition. Rockfall and sliding of angular blocks was observed at this location. The protalus rampart forms a contact zone between the active talus and inactive rock glacier.

Alluvial and lacustrine deposits occur within the catchment. All stream channels contain some variably thick unconsolidated materials. Modern deposits include bars, channel lag, floodplain aggradation, and outwash. Most modern stream deposits lacked sufficient width to be portrayed on the surficial map.

Two lacustrine deposits exist within the catchment. One deposit exists in a large depression located on the southern catchment boundary at 2012 m (6636 ft). This depression is interpreted to have been closed at its lower end by ice, debris, and/or till during the late Pleistocene and Holocene. This is evidenced by the location of a large lateral moraine which connects with a ridge forming outcrop, and by the coarse textured alluvial flood deposits that exist immediately below the depression. The depression contains seeping and standing waters for several months of the year. Pits were dug to retrieve material from beneath organic muck, but no samples were successfully collected. Fine sand, silt, and clay deposition occurs within the sedge and willow vegetation.
The second lacustrine deposit was inspected after the large Maynard Creek pond, located at 1833 m (6050 ft), was drained. The uppermost sediments consisted of interbedded fine and very fine sands. The pond bed has a continuous layer of very fine sediment of undetermined thickness and is likely to have a very low hydraulic conductivity. Two additional lacustrine deposits exist very near the northern catchment boundary. These deposits exist in operational waste-water lagoons and were not manually inspected.

Colluvial deposits in the Maynard Creek catchment consist primarily of talus aprons and talus cones. The coarse materials have been transported from steep rock slopes to their present position at the base of prominent outcrops and cliffs by free fall and slopewash. Finer material has been deposited in the interstitial spaces between larger clasts. This material has been transported to the talus slopes by slopewash, avalanche, and wind. Some fine material is formed in place by granular disintegration of coarse materials or by crushing of the coarse materials from subsequent rockfall onto the slope. The resulting deposits have formed slopes with linear profiles and minor upward concavity at their bases.

At several sites, soil pits were excavated and the profiles were inspected. In general, the talus materials have closed, clast-supported or matrix-supported fabrics. Mid-talus deposits display tight compaction and apparent sealing at depths of 20 cm (8 in) to 30 cm (12 in). It is commonly known that talus slopes trap finer particles at higher topographic positions while coarse clasts tumble to lower elevations (Selby, 1982). This sorting process operates on talus slopes in the Maynard Creek catchment.

Mass wasting deposits are defined by their material type and formative process as described by Varnes (1978). Individual mass wasting deposits are most easily distinguished by the texture class and the mechanisms of failure. The most common types of failures in the catchment are falls, rotational slumps, translational slides, and flows.

Rockfall is common where Mission Canyon limestone is undercut by preferential erosion of the underlying (up-section) Amsden-Big Snowy strata. Much of the rockfall
likely occurred after the final glacial retreat, when supportive buttressing from ice masses was removed. Mega-blocks topple from locations where fracturing is extensive and jointing planes are near vertical. The deposits consist of large, poorly sorted, matrix-poor, angular blocks that have a fan shape or form a thin veneer of scattered boulders. Recent, angular deposits thinly cover materials of glacial or colluvial origin.

Rotational slumping of unconsolidated debris is common. Slumps typically occur in either undifferentiated glacial till or the weathered Morrison formation. A spoon- or bowl-shaped failure surface is the most distinctive characteristic of slumps. The deposits often display a prominent lobate shape, have an elevated toe-slope, and have a convex long profile at their lower end.

Translational slides occur in bedrock and surficial deposits. Translational failure is common on deeply weathered planar slopes, where soil, regolith, and other deposits slide across an underlying bedrock surface. The limited material displacement in translational failures produces shallow surface features. In general, the failure surface long profiles are planar, and the width profiles display shallow "V" or "U" shapes.

Flows are common in debris and earthen material. Two small earthflows exist in the upper catchment. One feature is very flat, displays lateral ridges, and is naturally occurring. The other earth flow resulted from road construction through Amsden strata where abundant fine grained, loose material washed off the disturbed site.

The largest individual mass wasting deposit resulted from a debris flow that came to rest at the bottom of the catchment. The broad fan-like surface has subdued lateral ridges on its north and south margins. The deposit occupies high swales along its margins. Also, the materials exist north of the drainage divide in isolated debris piles adjacent to the low points of the divide. Twelve backhoe pits dug in the central portion of the deposit were described in detail by Schafer and Associates (1990).
Boulders of Paleozoic and Mesozoic rocks are most common on the surface and at depth. The clasts are angular to subrounded and poorly sorted. Sorting of bouldery material and localized channeling exists in the unstratified deposit which is known to be 2 m (6.6 ft) to 4 m (13.2 ft) thick. Large clasts dominate the deepest level of the deposit, and the material exhibits a distinct fining-upward gradation at one location (Schafer and Associates, 1990). Imbrication was noted at one site, and the preferred orientation was N 25°E and 47°W. The matrix-supported deposit consists of 40% to 60% medium clay and has silt loam and silty clay loam soils. Fine-grained soils at the northern margin become coarser as one moves south into the interior of the deposit (Schafer and Associates, 1990).

Other unique surficial hydrogeologic features have been located. They include sieve-like recharge drains, linear depressions, extensive animal burrowing networks, piping, sapping, and artesian flow. These features are discussed later in the interpretation of the character of surficial Quaternary aquifer systems.

Hydrogeologic Mapping

Three categories of hydrogeologic features have been distinguished and mapped. They are spring distributions, stream networks, and other surface waters (Plate 3). The individual spring symbols define the location of springs as they were mapped on June 20 and June 21, 1991. Some springs were not located until after June 21, but they are also included on Plate 3.

At several locations individual spring discharge points shifted several meters. This phenomenon occurred within sediment-filled stream channels when late summer discharge points changed position. The points of emergence always moved down-gradient.

At four locations, water flowed from exposed bedrock. All four springs displayed low yield from fractures and a short duration of flow. All other springs flowed from discharge points in unconsolidated Quaternary materials.
Stream networks were mapped where the maximum upslope extent of channelized flow was observed. In this study, the order of streams was determined during the early summer months of 1990 and 1991. Ephemeral channels were not mapped. Zero-order stream flow occurs where springs and/or seeps drain into poorly developed channels. First-order streams occur at the uppermost reaches of well-defined stream channels, where stream flow is sustained for several weeks to several months by the combined flow of several zero-order flows. The first-order streams are intermittent or perennial. Second-order streams occur where two or more first-order streams join. The third-order stream in the catchment (Maynard Creek) is perennial, and begins where two second-order streams join.

Surface water features have been categorized into four mapping units: seeps, standing waters, natural ponds, and engineered ponds. Seeps discharge overland flow from diffuse zones of saturated surficial materials. Standing water is surface runoff that concentrates in shallow depressions. Two small natural ponds (< 100 m², 1089 ft²) are contained by separate mass wasting deposits.

Four engineered ponds were mapped. Two ponds are located north of Maynard Creek at 1845 m (6050 ft) and function as waste-water lagoons for the Bridger Pines Subdivision. A third and largest pond impounds Maynard Creek at 1845 m (6050 ft). At this location, runoff is stored during winter months, and occasionally diverted for snow-making at Bridger Bowl Ski Area. The pond has limited recreational amenities. The fourth and smallest pond is located at 1924 m (6310 ft) and is maintained by snowmelt and seepage that is diverted with small ditches and water bars.
Aquifer Material Characterization

Surficial Materials and Potential Aquifers

Two areas were identified as probable surficial, unconsolidated Quaternary aquifers. These areas are referred to later as the Bridger and Deer Park aquifers. These areas received special attention due to the presence of highly productive spring clusters and seeps which were located immediately below and within thick surficial materials. Seismic investigations, site examinations, and spring water sampling and monitoring were completed at both areas. Close inspection of these two areas produced results that enabled further aquifer characterization.

Existing Research

Published values of porosity, storativity, and hydraulic conductivity are reported in Table 1. These values are used to characterize surficial aquifer materials located in the Maynard Creek catchment.

Seismic Refraction

Twenty-four seismic refraction transects were arranged in close proximity to the Bridger and Deer Park groundwater discharge areas (Figures 4 and 5). Selected time-distance diagrams constructed from seismic first-arrival data are depicted in Figures 6 through 9. The seismic velocities and calculated depths to second layers for all seismic lines are displayed in Table 2. A histogram of velocity classes demonstrates the distribution of seismic velocities of geological materials found in the study area (Figure 10). Published seismic velocities of geologic materials are summarized in Table 3.
TABLE 1. PUBLISHED ESTIMATED VALUES OF POROSITY, STORATIVITY, AND HYDRAULIC CONDUCTIVITY FOR UNCONSOLIDATED MATERIALS.

<table>
<thead>
<tr>
<th>Material Type</th>
<th>Porosity (%)</th>
<th>Storativity (%)</th>
<th>Hydraulic Conductivity (m/d)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Clay</td>
<td>42(1)</td>
<td>3(2)</td>
<td>$10^{-5}$ (massive clay)(7)</td>
</tr>
<tr>
<td></td>
<td>45-55(8)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Silt</td>
<td>46(1)</td>
<td>8(2)</td>
<td>$10^{-3}$ to $10^{-2}$ (silt/clay, mix of sand, silt, clay)(7)</td>
</tr>
<tr>
<td></td>
<td>35-50(8)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sand (fine to coarse)</td>
<td>43-39(1)</td>
<td>23-27(2)</td>
<td>$1 \times 10^1$ (fine sand)(7)</td>
</tr>
<tr>
<td></td>
<td>25-40(8)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Gravel (sand/gravel)(7) (fine to coarse)</td>
<td>28-34(1)</td>
<td>23-25(2)</td>
<td>$10^1$ to $10^2$</td>
</tr>
<tr>
<td></td>
<td>25-40(8)</td>
<td></td>
<td>$10^3$ to $10^4$ (clean grav)(7)</td>
</tr>
<tr>
<td>Till (mainly silt/clay)</td>
<td>34(1)</td>
<td>6(2)</td>
<td>$10^{-3}$ to $1(6)$</td>
</tr>
<tr>
<td></td>
<td>10-25(8)</td>
<td>&lt;5(2)</td>
<td>$10^{-6}$ to $10^2$(8)</td>
</tr>
<tr>
<td></td>
<td>25-45(3)</td>
<td></td>
<td>$10^{-6}$ to $10^{-4}$(5)</td>
</tr>
<tr>
<td>Outwash (sorted)</td>
<td></td>
<td></td>
<td>$10^2$ to $10^4$(4) up to $10^1$(3)</td>
</tr>
<tr>
<td>Mass Wastling (debris flow)</td>
<td></td>
<td></td>
<td>$10^{-4}$ to $10^1$(9)</td>
</tr>
</tbody>
</table>

Figure 4. The Bridger groundwater discharge investigation area.

Figure 5. The Deer Park groundwater discharge investigation area.
Figure 6. Time-distance diagram for seismic Line 8. Depiction of a two-layer stratigraphy.

Figure 7. Time-distance diagram for seismic Line 17. Depiction of a three-layer stratigraphy.
Figure 8. Time-distance diagram for seismic Line 14. Depiction of a two-layer stratigraphy and a low-velocity discontinuity.

Figure 9. Time-distance diagram of seismic Line 19. Depiction of a two-layer stratigraphy and a low-velocity discontinuity.
### TABLE 2. SEISMIC VELOCITIES AND CALCULATED DEPTHS OF MATERIALS IN THE MAYNARD CREEK CATCHMENT.

<table>
<thead>
<tr>
<th>Line</th>
<th>Layer</th>
<th>Velocity (m/s)</th>
<th>Depth(s) (m)</th>
<th>Line</th>
<th>Layer</th>
<th>Velocity (m/s)</th>
<th>Depth(s) (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1*</td>
<td>1</td>
<td>&lt;295</td>
<td>2.1</td>
<td>13</td>
<td>1</td>
<td>348</td>
<td>2.7, 1.8</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>1590</td>
<td></td>
<td></td>
<td>2</td>
<td>1818</td>
<td></td>
</tr>
<tr>
<td>2*</td>
<td>1</td>
<td>286</td>
<td>4.8</td>
<td>14</td>
<td>1</td>
<td>444</td>
<td>3.3</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>2272</td>
<td></td>
<td></td>
<td>2</td>
<td>1648</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>1</td>
<td>308</td>
<td>1.4, 2.8</td>
<td>15</td>
<td>1</td>
<td>444</td>
<td></td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>702</td>
<td></td>
<td></td>
<td>2</td>
<td>909</td>
<td></td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>2721</td>
<td></td>
<td></td>
<td>3</td>
<td>3810</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>1</td>
<td>354</td>
<td>3.5, 4.4</td>
<td>16</td>
<td>1</td>
<td>286</td>
<td>3.1, 2.1</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>1364</td>
<td></td>
<td></td>
<td>2</td>
<td>2824</td>
<td></td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>3000</td>
<td></td>
<td></td>
<td>1</td>
<td>286</td>
<td>1.9, 3.3</td>
</tr>
<tr>
<td>5</td>
<td>1</td>
<td>286</td>
<td>3.9, 2.9</td>
<td>17</td>
<td>1</td>
<td>1091</td>
<td></td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>1787</td>
<td>2.3, 3.2</td>
<td></td>
<td>2</td>
<td>3294</td>
<td></td>
</tr>
<tr>
<td>6</td>
<td>1</td>
<td>297</td>
<td>1.7, 1.9</td>
<td>18</td>
<td>2</td>
<td>381</td>
<td>3.5, 4.3</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>1025</td>
<td></td>
<td></td>
<td>2</td>
<td>1905</td>
<td></td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>2824</td>
<td></td>
<td></td>
<td>1</td>
<td>400</td>
<td>2.6</td>
</tr>
<tr>
<td>7</td>
<td>1</td>
<td>365</td>
<td>3.3, 5.2</td>
<td>19</td>
<td>2</td>
<td>2431</td>
<td></td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>2105</td>
<td>4.8, 2.4</td>
<td></td>
<td>2</td>
<td>333</td>
<td>2.7, 4.8</td>
</tr>
<tr>
<td>8</td>
<td>1</td>
<td>372</td>
<td>2.1, 3.4</td>
<td>20</td>
<td>1</td>
<td>1389</td>
<td></td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>1600</td>
<td>3.8, 3.1</td>
<td></td>
<td>2</td>
<td>355</td>
<td>5.2, 3.4</td>
</tr>
<tr>
<td>9</td>
<td>1</td>
<td>363</td>
<td>2.2, 1.5</td>
<td>21</td>
<td>1</td>
<td>1818</td>
<td></td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>1805</td>
<td></td>
<td></td>
<td>2</td>
<td>381</td>
<td></td>
</tr>
<tr>
<td>10</td>
<td>1</td>
<td>348</td>
<td>2.1</td>
<td>22</td>
<td>1</td>
<td>381</td>
<td></td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>1872</td>
<td></td>
<td></td>
<td>2</td>
<td>2162</td>
<td></td>
</tr>
<tr>
<td>11*</td>
<td>1</td>
<td>323</td>
<td>2.1</td>
<td>23</td>
<td>1</td>
<td>421</td>
<td>4.0, 3.5</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>1818</td>
<td></td>
<td></td>
<td>2</td>
<td>1379</td>
<td></td>
</tr>
<tr>
<td>12</td>
<td>1</td>
<td>1314</td>
<td>3.9, 2.6</td>
<td>24</td>
<td>1</td>
<td>459</td>
<td>4.6, 8.0</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>1399</td>
<td></td>
<td></td>
<td>2</td>
<td>&lt;8000</td>
<td></td>
</tr>
</tbody>
</table>

(*) denotes no reverse shooting.
Figure 10. Frequency and distribution of seismic velocities of materials located in the Bridger and Deer Park groundwater discharge areas.

### TABLE 3. PUBLISHED SEISMIC VELOCITIES OF GEOLOGIC MATERIALS.

<table>
<thead>
<tr>
<th>Materials</th>
<th>Velocity (m/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Modern Alluvium (2)(4)</td>
<td>350 - 400</td>
</tr>
<tr>
<td>&quot;Soil&quot; (packed)(1)</td>
<td>460 - 600</td>
</tr>
<tr>
<td>&quot;Soil&quot; (normal)(1)</td>
<td>240 - 460</td>
</tr>
<tr>
<td>Embankments and Fill(3)</td>
<td>400</td>
</tr>
<tr>
<td>Loose Gravel (wet)(1)</td>
<td>460 - 915</td>
</tr>
<tr>
<td>Loose Sand and Gravel (wet)(1)</td>
<td>460 - 1 220</td>
</tr>
</tbody>
</table>

Continued on next page
TABLE 3. PUBLISHED SEISMIC VELOCITIES OF GEOLOGIC MATERIALS.  
- Continued.

<table>
<thead>
<tr>
<th>Materials</th>
<th>Velocity (m/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Older Alluvium (2)(5)</td>
<td>710 - 810</td>
</tr>
<tr>
<td>Saturated Alluvium (4)(5)</td>
<td>1 580 - 1 640</td>
</tr>
<tr>
<td>Glacial Till (undifferentiated, unsaturated)(3)</td>
<td>430 - 1 040</td>
</tr>
<tr>
<td>Glacial Till (undifferentiated, saturated)(3)</td>
<td>1 670</td>
</tr>
<tr>
<td>Pinedale Till (2)(5)</td>
<td>710 - 1 070</td>
</tr>
<tr>
<td>Bull Lake II Till (2)</td>
<td>910 - 930</td>
</tr>
<tr>
<td>Bull Lake I Till (2)</td>
<td>970 - 1 140</td>
</tr>
<tr>
<td>Sandstone and Shale (Tertiary)(3)</td>
<td>2 100 - 3 500</td>
</tr>
<tr>
<td>Sandstone and Shale (Cretaceous)(3)</td>
<td>2 400 - 3 900</td>
</tr>
<tr>
<td>Shale (soft)(1)</td>
<td>220 - 2 135</td>
</tr>
<tr>
<td>Shale (hard)(1)</td>
<td>1 830 - 2 740</td>
</tr>
<tr>
<td>Sandstone (soft)(1)</td>
<td>1 525 - 2 135</td>
</tr>
<tr>
<td>Sandstone (hard)(1)</td>
<td>1 830 - 3 050</td>
</tr>
<tr>
<td>Limestone (soft)(3)</td>
<td>1 700 - 4 200</td>
</tr>
<tr>
<td>Limestone (hard)(3)</td>
<td>2 800 - 6 400</td>
</tr>
<tr>
<td>Quartzite (3)</td>
<td>6 100</td>
</tr>
<tr>
<td>Steel (3)</td>
<td>5 900 - 6 400</td>
</tr>
</tbody>
</table>

The seismic velocities of visually determined material types were calculated for individual lines in the Bridger and Deer Park groundwater discharge areas. The velocity of the reworked backfill material at Line 1 was 295 m/s (974 ft/s). Line 11 was completed within an excavation pit, where 2 m (6.6 ft) of weathered till with soil structure and weathered shale were exposed. The weathered till displayed a velocity of 323 m/s (1066 ft/s) and the weathered shale had a velocity of 1818 m/s (5999 ft/s). Lines 9 and 22 were run along "two-track", unimproved road surfaces. The average seismic velocity for the road surfaces was 373 m/s (1242 ft/s). Lines 16 and 17 were completed along surfaces that were covered by thick forest litter or "duff". The seismic velocity of this soil layer was 286 m/s (944 ft/s). Line 17 was run across Cretaceous sandstone from the Sedan Group which was well exposed immediately above the transect. The seismic velocity of this sandstone was 3294 m/s (10,870 ft/s).

The range of thickness of first layer materials is 1.5 m (5 ft) to 8 m (26.4 ft) with an average thickness of 3.4 m (11.2 ft), as calculated by time-intercept and time-delay methods from forty-one points. The range and average seismic velocities of all materials are summarized in Table 4.

Site Examination

Soils and subsoils were sampled by mechanical coring and auguring, excavation, and hand digging. The materials were sampled from groundwater discharge zones and from unique geomorphologic deposits.

A Giddings soil sampler was used to extract surficial Quaternary materials from the Bridger groundwater discharge area. Drilling on a single transect intersected a linear depression that is connected to several prominent springs (Figure 4, p. 39). The site displays a morphology that indicates the existence of a sub-surface channel. The drilling depth to groundwater was recorded.
TABLE 4. THE RANGE AND AVERAGE SEISMIC VELOCITIES OF SPECIFIC GEOLOGIC MATERIALS IN THE MAYNARD CREEK CATCHMENT.

<table>
<thead>
<tr>
<th>Material</th>
<th>Range of Velocity (m/s)</th>
<th>Average Velocity (m/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Forest Litter Soils</td>
<td>286 - 286</td>
<td>286, n = 2</td>
</tr>
<tr>
<td>Man Altered Fill</td>
<td>267 - 372</td>
<td>325, n = 13</td>
</tr>
<tr>
<td>Undisturbed Till Soils</td>
<td>323 - 459</td>
<td>415, n = 6</td>
</tr>
<tr>
<td>Young Till</td>
<td>702 - 762</td>
<td>732, n = 2</td>
</tr>
<tr>
<td>Older Till</td>
<td>909 - 1119</td>
<td>1038, n = 5</td>
</tr>
<tr>
<td>Weathered Sandstone / Shale</td>
<td>1364 - 1905</td>
<td>1659, n = 14</td>
</tr>
<tr>
<td>Sandstone and Shale</td>
<td>2105 - 3810</td>
<td>2744, n = 10</td>
</tr>
</tbody>
</table>

Eighteen drill holes were attempted, and thirteen disturbed subsoil samples were retrieved. The maximum drilling depth was 140 cm (87 in) and all samples sustained significant compaction or fracturing. In general, the collected materials were poorly sorted and very clayey. Rock content was high and most holes terminated when rock was encountered. Drilling at one site intersected saturated materials in all three holes (three holes per set-up site) at depths of approximately 165 cm (65 in) to 190 cm (75 in). All remaining holes were dry.

Soil pits were completed in undifferentiated till, glacial outwash, mass wasting debris, and talus. The descriptions of these materials are included in Results: Geomorphological Mapping. The undifferentiated till displayed fine soil fractures in well developed soils. The texture and fabric of these tills are highly variable. Animal burrows were common at shallow depths (< 0.5 m, 1.6 ft) where moist swales are thickly
vegetated. Also, piping occurs in soils developed on the undifferentiated tills. Examples of this material are displayed in Figure 11.

Outwash was exposed during culvert installation. This material consisted of clast-supported, moderately sorted, subangular to subrounded cobbles, and a fine to medium sand and fine gravel matrix (Figure 12, left).

Unconsolidated material was collected during the construction of a spring development. Backhoe excavation and hand digging of a meter of overburden exposed coarse, angular, well sorted, small to medium cobble, and large gravel material. The material was nearly free of fine particles. The loosely packed material was extracted from a symmetrical, channel-shaped lense located beneath the till overburden (Figure 12, right). These springhead source materials form a unique deposit contained within the finer textured undifferentiated till.

Soil pits in mass wasting deposits were inspected at a few locations throughout the catchment. The materials display a broad range of characteristics. The earthen deposits are fine-grained and contained animal burrows and soil piping. Debris deposits are fragmental and rock deposits contain very little fine matrix.

Talus was inspected in the "South Bowl" area (Figure 2, p. 4) at five pits on the largest talus cone located below a prominent central gully. Apparently, surface runoff occurs in large volumes as evidenced by the numerous large gullies on the deposits. The material consisted of assorted angular rock fragments with interstitial spaces completely filled and tightly sealed at shallow depths.

Two percolation tests were completed in a moraine near the Bridger groundwater discharge area. The tests were completed for the purposes of a drain field design and septic system installation. The results were percolation rates of 0.35 m/d (1.2 ft/d) to 0.40 m/d (1.3 ft/d). This percolation rate represents the unsaturated flow velocity of infiltrating surface water in undifferentiated morainal till.
Figure 11. Examples of texture of two separate undifferentiated tills.

Figure 12. Outwash (left) and buried deposits (right) at a springhead.
Hydrology

Existing Data

Previous investigators have gathered stream discharge data from Maynard Creek (Williams, 1967; Morrison-Maierle, Inc., 1978). A stream hydrograph has been constructed from data collected by Williams (1967) (Figure 13). These results, in conjunction with information gathered during this study, will be used to interpret water storage characteristics of the Maynard Creek catchment. Hydrologic data collection sites from other investigations and those used during this study are displayed in Figure 14.

Figure 13. Stream hydrograph for Maynard Creek (after Williams, 1967).
Figure 14. Location of sites, facilities, and measurement points.

- well
- spring
- stream
- stream discharge
- USWB Bozeman 12 NE station
- NRCS SNOTEL station
- Maynard Creek site
- Bridger Bowl site
- perennial spring cluster
- Bridger investigation area
- Deer Park investigation area
The U.S.G.S. calculated average monthly flows of Maynard Creek based on a seasonally variable percentage of Bridger Creek discharges during 27 years of record (Morrison-Maierle, Inc., 1978) (Table 5). The estimated minimum depicts extreme low flow conditions.

<table>
<thead>
<tr>
<th>Month</th>
<th>Maximum (acre-ft)</th>
<th>Minimum (acre-ft)</th>
<th>Estimated Minimum (1934-37)</th>
</tr>
</thead>
<tbody>
<tr>
<td>October</td>
<td>137</td>
<td>37</td>
<td>21</td>
</tr>
<tr>
<td>November</td>
<td>129</td>
<td>34</td>
<td>20</td>
</tr>
<tr>
<td>December</td>
<td>105</td>
<td>25</td>
<td>20</td>
</tr>
<tr>
<td>January</td>
<td>85</td>
<td>16</td>
<td>12</td>
</tr>
<tr>
<td>February</td>
<td>130</td>
<td>11</td>
<td>8</td>
</tr>
<tr>
<td>March</td>
<td>192</td>
<td>12</td>
<td>10</td>
</tr>
<tr>
<td>April</td>
<td>309</td>
<td>42</td>
<td>24</td>
</tr>
<tr>
<td>May</td>
<td>1434</td>
<td>232</td>
<td>58</td>
</tr>
<tr>
<td>June</td>
<td>1429</td>
<td>193</td>
<td>50</td>
</tr>
<tr>
<td>July</td>
<td>720</td>
<td>93</td>
<td>24</td>
</tr>
<tr>
<td>August</td>
<td>379</td>
<td>38</td>
<td>20</td>
</tr>
<tr>
<td>September</td>
<td>244</td>
<td>44</td>
<td>22</td>
</tr>
</tbody>
</table>

The Natural Resources Conservation Service has maintained records of snow-water equivalent at two SNOTEL stations in the Maynard Creek catchment (Figure 14, p. 50). The recorded snow-water equivalent from the Maynard Creek station, located at 1893 m (6210 ft), and the Bridger Bowl station, located at 2210 m (7250 ft), represent the
accumulation and loss of snowpack throughout the year. The snow-water equivalents of
snowpacks at the Maynard Creek and Bridger Bowl stations during the months of this
investigation are compared to 30-year averages from 1961 through 1990 (Figure 15, 16).

Long-term meteorological records are maintained at the United States Weather Bureau
Bozeman 12 NE Station (Figure 14, p. 50). Selected data collected at the station is used to
interpret the influence of meteorology on the local hydrologic regime. The average daily
temperature has been plotted for part of the duration of this investigation (Figure 17). The
long-term mean annual air temperature at the Bozeman 12 NE Station is 3.3°C (37.9°F)
(Moore, 1984).

Figure 15. Snow-water equivalent of snowpack, Maynard Creek SNOTEL Station,
Figure 16. Snow-water equivalent of snowpack, Bridger Bowl SNOTEL Station, water years 1990 and 1991 compared to 30-year average (1961-1990).

Figure 17. Mean daily air temperature measured at the United States Weather Bureau Bozeman 12 NE Station, Maynard Creek catchment, 1805 m (5920 ft).
Stream Discharge Measurements

Stream discharge measurements on the north and south forks of Maynard Creek have been used to construct a trailing limb for each stream hydrograph (Figure 18). The discharge measurements were completed on the two uppermost perennial stream reaches located immediately below perennial springs (Figure 14, p. 50). The hydrographs depict winter baseflow conditions. The cross-sectional area of each stream increased notably over short distances downstream, although few places remained ice-free and accessible. These stream discharge observations indicate that discharge increases with distance downstream along the reaches located immediately below the north and south fork measurement sites.

Figure 18. Stream discharge (l/s) for the north and south forks of Maynard Creek.
Water Chemistry

Existing Data

Previous investigators analyzed well, spring, and creek waters taken from study area. Specific collection sites and analyses number are shown in Figure 14 (p. 50). Well water analyses are listed in Table 6. Spring and creek analyses are listed in Table 7.

<table>
<thead>
<tr>
<th>Source</th>
<th>Ca (meq/l)</th>
<th>Mg</th>
<th>Na</th>
<th>K</th>
<th>HCO₃</th>
<th>Cl</th>
<th>SO₄</th>
<th>Fe</th>
<th>TDS (mg/l)</th>
<th>pH</th>
<th>SC (mS)</th>
</tr>
</thead>
<tbody>
<tr>
<td>W1a</td>
<td>0.93</td>
<td>0.20</td>
<td>0.98</td>
<td>0.0</td>
<td>1.68</td>
<td>0.03</td>
<td>0.23</td>
<td>&lt;0.01</td>
<td>160</td>
<td>7.9</td>
<td>0.21</td>
</tr>
<tr>
<td>W1b</td>
<td>0.70</td>
<td>0.0</td>
<td>3.05</td>
<td>0.0</td>
<td>2.36</td>
<td>0.0</td>
<td>0.23</td>
<td>&lt;0.01</td>
<td>---</td>
<td>7.7</td>
<td>---</td>
</tr>
<tr>
<td>W1c</td>
<td>0.80</td>
<td>0.25</td>
<td>2.92</td>
<td>0.0</td>
<td>---</td>
<td>---</td>
<td>2.00</td>
<td>&lt;0.01</td>
<td>---</td>
<td>8.6</td>
<td>---</td>
</tr>
<tr>
<td>W1d</td>
<td>0.60</td>
<td>0.25</td>
<td>0.26</td>
<td>0.0</td>
<td>1.03</td>
<td>0.23</td>
<td>0.13</td>
<td>---</td>
<td>104</td>
<td>6.4</td>
<td>---</td>
</tr>
<tr>
<td>W1e</td>
<td>0.60</td>
<td>0.25</td>
<td>0.17</td>
<td>0.03</td>
<td>1.18</td>
<td>0.03</td>
<td>0.06</td>
<td>0.02</td>
<td>103</td>
<td>6.9</td>
<td>---</td>
</tr>
<tr>
<td>W1f</td>
<td>0.76</td>
<td>0.28</td>
<td>0.20</td>
<td>---</td>
<td>1.16</td>
<td>0.01</td>
<td>0.12</td>
<td>0.03</td>
<td>---</td>
<td>6.8</td>
<td>---</td>
</tr>
<tr>
<td>W2</td>
<td>0.60</td>
<td>0.0</td>
<td>0.39</td>
<td>---</td>
<td>1.25</td>
<td>---</td>
<td>---</td>
<td>---</td>
<td>---</td>
<td>7.5</td>
<td>---</td>
</tr>
<tr>
<td>W3</td>
<td>1.38</td>
<td>0.49</td>
<td>0.55</td>
<td>---</td>
<td>2.18</td>
<td>0.06</td>
<td>0.18</td>
<td>0.03</td>
<td>---</td>
<td>7.6</td>
<td>---</td>
</tr>
<tr>
<td>W4</td>
<td>0.59</td>
<td>0.10</td>
<td>1.44</td>
<td>---</td>
<td>1.96</td>
<td>0.01</td>
<td>0.21</td>
<td>0.04</td>
<td>175</td>
<td>8.0</td>
<td>0.21</td>
</tr>
</tbody>
</table>
The water samples from previous investigations were collected and analyzed with unknown methods over several decades. In several cases, the analyses were incomplete or the concentrations of dissolved solids was below the level of detection. A lack of sufficient or accurate data for many of these analyses renders them inadequate for interpretation. The analyses used for interpretations in this study have balanced cation:anion ratios (Domenico and Schwartz, 1989).

TABLE 7. CHEMICAL ANALYSES OF WATERS COLLECTED FROM SPRINGS OR CREEKS FROM WITHIN OR NEAR THE MAYNARD CREEK CATCHMENT. S1 = Bridger Pines NW spring, prior to 7-11-91; S2 = Deer Park spring, 10-6-77; S3 = St. Bernard spring, 10-6-77. C1 = Bridger Creek headwaters, 2-28-84; C2: a,b = Bridger Creek above Maynard Creek, 2-28-84, 10-6-77; C3 = Bridger Creek tributary above Bridger Pines sewage lagoon, 5-21-84; C4 = Bridger Creek tributary below Bridger Pines sewage lagoon, 5-21-84; C5 = Maynard Creek Day Lodge intake, 10-6-77; C6 = Maynard Creek near mouth, 10-6-77. — indicates no data.

<table>
<thead>
<tr>
<th>Source</th>
<th>Ca</th>
<th>Mg</th>
<th>Na</th>
<th>K</th>
<th>HCO3</th>
<th>Cl</th>
<th>SO4</th>
<th>Fe</th>
<th>TDS</th>
<th>pH</th>
<th>SC</th>
</tr>
</thead>
<tbody>
<tr>
<td>S1</td>
<td>0.54</td>
<td>0.18</td>
<td>0.22</td>
<td>&lt;0.03</td>
<td>0.85</td>
<td>&lt;0.03</td>
<td>0.25</td>
<td>0.03</td>
<td>76</td>
<td>6.0</td>
<td>0.11</td>
</tr>
<tr>
<td>S2</td>
<td>2.75</td>
<td>1.07</td>
<td>0.17</td>
<td>---</td>
<td>3.79</td>
<td>---</td>
<td>0.12</td>
<td>---</td>
<td>---</td>
<td>7.8</td>
<td>---</td>
</tr>
<tr>
<td>S3</td>
<td>3.44</td>
<td>1.18</td>
<td>0.19</td>
<td>---</td>
<td>4.75</td>
<td>---</td>
<td>0.10</td>
<td>Tr.</td>
<td>---</td>
<td>7.9</td>
<td>---</td>
</tr>
<tr>
<td>C1</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>0.03</td>
<td>0.0</td>
<td>0.0</td>
<td>---</td>
<td>8.4</td>
<td>0.30</td>
</tr>
<tr>
<td>C2a</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>0.02</td>
<td>0.0</td>
<td>0.0</td>
<td>---</td>
<td>8.2</td>
<td>0.22</td>
</tr>
<tr>
<td>C2b</td>
<td>1.61</td>
<td>0.55</td>
<td>0.27</td>
<td>0.0</td>
<td>2.34</td>
<td>0.06</td>
<td>0.10</td>
<td>&lt;0.01</td>
<td>---</td>
<td>8.1</td>
<td>---</td>
</tr>
<tr>
<td>C3</td>
<td>0.0</td>
<td>0.0</td>
<td>0.13</td>
<td>0.0</td>
<td>0.0</td>
<td>0.03</td>
<td>0.0</td>
<td>0.0</td>
<td>---</td>
<td>---</td>
<td>0.07</td>
</tr>
<tr>
<td>C4</td>
<td>0.0</td>
<td>0.0</td>
<td>0.14</td>
<td>0.0</td>
<td>0.0</td>
<td>0.04</td>
<td>0.0</td>
<td>0.0</td>
<td>---</td>
<td>---</td>
<td>0.07</td>
</tr>
<tr>
<td>C5</td>
<td>0.31</td>
<td>3.53</td>
<td>0.17</td>
<td>0.0</td>
<td>3.92</td>
<td>0.03</td>
<td>0.10</td>
<td>Tr</td>
<td>---</td>
<td>8.0</td>
<td>---</td>
</tr>
<tr>
<td>C6</td>
<td>0.05</td>
<td>0.83</td>
<td>0.18</td>
<td>0.0</td>
<td>3.80</td>
<td>0.01</td>
<td>0.10</td>
<td>Tr</td>
<td>---</td>
<td>8.2</td>
<td>---</td>
</tr>
</tbody>
</table>
New Data

Chemical analyses of waters taken from two perennial springs for this study are listed in Table 8. The collection sites and analyses numbers are shown in Figure 14 (p. 50). Both springs discharge directly from surficial deposits.

<table>
<thead>
<tr>
<th>Source</th>
<th>Ca (meq/l)</th>
<th>Mg (mg/l)</th>
<th>Na (mg/l)</th>
<th>K (mg/l)</th>
<th>HCO3 (mg/l)</th>
<th>Cl (mg/l)</th>
<th>SO4 (mg/l)</th>
<th>Fe (mg/l)</th>
<th>TDS (mg/l)</th>
<th>pH</th>
<th>SC (mS)</th>
</tr>
</thead>
<tbody>
<tr>
<td>SS1</td>
<td>2.97</td>
<td>0.86</td>
<td>0.23</td>
<td>0.015</td>
<td>3.90</td>
<td>&lt;0.03</td>
<td>&lt;0.02</td>
<td>&lt;0.01</td>
<td>7.6</td>
<td></td>
<td>0.36</td>
</tr>
<tr>
<td>SS2</td>
<td>2.94</td>
<td>0.88</td>
<td>0.13</td>
<td>0.013</td>
<td>3.93</td>
<td>&lt;0.03</td>
<td>&lt;0.05</td>
<td>&lt;0.01</td>
<td>7.7</td>
<td></td>
<td>0.35</td>
</tr>
</tbody>
</table>

Spring Water Monitoring

Spring Inventory and Monitoring

The location, character, and duration of flow of individual springs, seeps, and related hydrogeologic features were recorded over two field seasons. During 1990, 49 springs were located. Early in the 1991 field season a total of 62 unique springs were identified (Plate 3). These springs were visited biweekly during each field season. The location, water temperature, discharge, and other characteristics were noted for each spring. Six additional springs were found immediately beyond the catchment boundary. These springs were observed and inventoried, but not regularly visited or used for data interpretations.
Spring Discharge

The discharge of all 62 springs was approximated and categorized into one of three discharge classes. Spring discharge ranged from approximately 0.06 lps (1 gpm) to greater than 18.9 lps (300 gpm). Figure 19 shows the total number of springs in each discharge class as observed on three different dates of observation. The Deer Park spring (Spring 23) was the most productive perennial spring identified during this investigation, and was most frequently monitored throughout the duration of this investigation. Measurements of the Deer Park spring discharge were used to construct a spring hydrograph (Figure 20). The most frequent monitoring of the Deer Park spring was completed during snowmelt runoff periods in order to define a relationship between surface water recharge and spring discharge. A few low yield, very short duration springs that dried up during early summer were briefly reactivated after intense rainstorm events. This indicates the ephemeral nature of several spring discharge points in the catchment.

Specific Electrical Conductance

The specific electrical conductance of all spring waters discharging into the Maynard Creek catchment were measured during a single field season. The SC values ranged from 0.16 to 0.50 millisiemens (mS). The measurements were completed on June 21, 1991. The meter probe failed in July and SC measurements were discontinued for the remainder of the field season. Failure of the probe prevented the collection of data that would have defined the temporal variability in ionic concentrations of total dissolved solids within spring waters.
Figure 19. The discharge class distribution of springs at three different times of observation. Class 1 = 0.06 - <0.32 lps (1 - <5 gpm), Class 2 = 0.32 - 1.26 lps (5 - 20 gpm), Class 3 = >1.26 lps (>20 gpm).

Figure 20. Deer Park spring hydrograph (Spring 23). Measurements taken between January 1, 1991 and June 7, 1992.
Spring Water Temperatures

The range of all spring water temperatures recorded during the period of observation is 1.9°C (35.4°F) to 9.6°C (49.3°F). The Deer Park spring was monitored throughout the year, although winter measurements were taken at widely spaced intervals. The spring water temperature regime of the Deer Park spring is shown in Figure 21. Water temperatures of two additional springs, each located at approximately the same elevation as Spring 23, are shown in Figure 22. Three springs, including Spring 23, each have distinct morphologic associations and widely separated locations, and displayed unique water temperature regimes (Figure 23).

Figure 21. Deer Park spring temperature variability, April 20, 1991 through June 7, 1992.
Figure 22. Temperature variability of springs located at similar elevations.

Figure 23. Three spring water temperature regimes of springs located at different elevations. The Deer Park Spring (23), a rock glacier spring (37), and a bedrock outcrop spring (51).
INTERPRETATIONS

Three questions must be answered to fulfill the purpose of this investigation. First, do surficial, unconsolidated Quaternary deposits perform as aquifers? Second, can one distinguish between surficial aquifer water and bedrock aquifer water? Finally, if the surficial materials are aquifers, can the aquifers be characterized? The interpretations of quantitative and qualitative information collected during this investigation are used to answer these questions.

Surficial, Unconsolidated Quaternary Aquifers

Interpretation of Mapping Results

A test of significance has been applied to the spatial pattern of spring distributions. The relationship between spring distribution and elevation was interpreted. The association of springs with landscape elements, landforms, and surficial Quaternary deposits was examined.

The Nearest Neighbor Index (Hammond and McCullagh, 1982) was used to test for non-random distribution of springs in the study area. Field mapping suggests that springs are not distributed randomly. The null hypothesis is $H_0$: the occurrence and distribution of springs is a pattern produced by independent random location. The alternative hypothesis is $H_1$: the spring distribution pattern is not random. The level of rejection is 0.01.

The index ranges from 0 (indicating that all points are closely clustered) to 2.15 (indicating that all points are uniformly distributed). A random distribution is indicated
when the index value approaches 1. To calculate the index value, two spring distribution patterns were used. All 62 known springs locations were used in the first test. Mid­summer spring locations (28 persistent springs) were used for the second test.

The index value, R, is calculated by dividing the mean-distance between nearest neighbor points in a given area, by the mean-distance expected from a similar number of points randomly distributed in the same area. The index value for 62 points is 0.31. The index value for 28 points is 0.43. These values indicate a strongly clustered spring distribution pattern.

The significance of these results can be tested with a technique described by King (1969). The technique produces a z-score of probability of a pattern occurring by chance. The calculated z-score was 10.15 for 62 points and 5.80 for 28 points. Although the z-scores are different, they both suggest that the probability of either spring distribution pattern occurring by chance is less than one in one thousand. This high level of significance justifies rejecting the null hypothesis and adopting the alternative hypothesis that spring distribution is not random.

The spring distribution pattern is also related to elevation. The distribution of springs is concentrated at lower elevations (Plate 3). The Maynard Creek catchment is funnel-shaped with the narrow end at lower elevations. Approximately half the catchment lies below 2121 m (7000 ft), but over 70% of the springs occur below this elevation. Nearly half of the springs lie below 2000 m (6600 ft), yet less than 20% of the catchment area is below 2000 m (6600 ft). About 75% of the mapped seeps, ponds, and standing water are located in the lower 20% of the catchment. In addition, the mapped extent of perennial stream flow approximately coincides with the 2000 m (6600 ft) elevation. Most groundwaters discharge below this elevation. The absence of extensive seepage zones and
abundant springs high on mountain slopes suggests that shallow groundwater flows into lower topographic positions occupied by surficial Quaternary deposits (Jamieson and Freeze, 1983).

Springs, seeps, and other groundwater outcrops are associated with landscape elements, landforms, and surficial Quaternary deposits. Springhead associations are divided into nine categories: 1) in bedrock (inferred); 2) in bedrock outcrops; 3) in uniform mid-slopes; 4) in buried channels; 5) in mass wasting deposits; 6) at base of moraines; 7) at the base of glacial outwash deposits; 8) below small sub-catchments; and 9) in active channels. The frequency of springs that occur in each morphologic category is shown in Figure 24.

![Figure 24. The frequency of springs in each morphologic category.](image)

The fact that only four springs discharge directly from bedrock outcrops is significant. One such spring discharges from the fault fractured Kootenai formation (Spring 11). The others flow from highly fractured Eagle sandstone (Spring 66) and the Sedan formation welded tuff (Springs 59 and 61). One spring (Spring 51) originates in thin regolith immediately below a prominent outcrop of the Sedan welded tuff, and was
inferred to discharge from this bedrock outcrop. No definitive evidence verified what aquifer type sustained Spring 51. Therefore, this spring has been classified to discharge from surficial deposits. All springs that discharged directly from bedrock had low yields and short flow duration. The remaining 57 springs discharge directly from surficial, unconsolidated Quaternary materials.

Two minor springs discharge from mid-slope positions on planar hillsides (Springs 5 and 35), and yielded less than 0.06 lps (5 gpm) each. Spring 5 emits flow from thick (>1 m, >3.3 ft) regolith and colluvium derived from the Eagle formation sandstone. The spring has little contributing area, and occurs on a broad slope formed by a ridge of Eagle sandstone. Spring discharge persisted at least from June through October. Spring 5 may be sustained by shallow, local groundwater storage in the mantle of regolith and colluvium, and in the highly fractured Eagle formation outcrop. Spring 35 flows from a broad and uniform slope covered by a thick blanket (>3 m, >9.9 ft) of clayey, undifferentiated till. Low discharge from soil piping was observed once in June and was probably sustained by soil water storage.

Buried channels were inferred during field mapping and are associated with springs at three locations. Springs 48 and 49 discharged from a single linear surface depression that is visible in the field and on a large-scale topographic map. This channel-like depression is thickly vegetated with willows and is connected to an active channel network. The channel-like feature was modified during ski area construction. Springs 48 and 49 are deeply incised (>3 m, >10 ft) in morainal till. The recessed concavities that contain the springheads have eroded headward; a phenomenon referred to by Higgins (1984) as sapping. Springs 48 and 49 are highly productive perennial springs and are discussed in further interpretations. Spring 50 is connected to an abandoned ephemeral channel which was partially buried by construction. This spring had low discharge and short flow duration.
Seven springs are associated with mass wasting deposits (Springs 9, 39, 43, 45, 46, 65, and 67). Seepage along the failure surface and point discharge near the toe of the deposits is common. Many springs that discharge from the mass wasting sites are associated with the Morrison formation and occur at higher elevations where surficial materials are generally thin. Piping and animal burrowing were observed in many of the mass wasting deposits. All seven springs had low yields and short flow durations.

Eleven springs discharged from the base of prominent moraines and moraine-like landforms (Springs 14, 15, 16, 17, 26, 33, 34, 37, 38, 44, and 58). The springheads all are positioned at the contact between the moraine toe and the underlying older till. In many cases the springheads are immediately below an enclosed depression or concavity (a recharge area) that is above and behind the moraine crest. One spring (Spring 37) is immediately down gradient from a closed depression and "drain hole" in the rock glacier. This and other conical pits in the rock glacier represent meltwater sinks similar to those described by Embleton and King (1968). In general, these springs were persistent with moderate to high yields.

The greatest number of springs (17) occur at the lower end of glacial outwash deposits. One of the deposits displays typical fan-like features and sustains six springs (Springs 27, 28, 29, 30, 31, and 32) and several seeps at its lower end, 1976 m (6520 ft). Two other spring clusters exist in outwash deposits. One is located at 1848 m (6100 ft) and the other one is at 2000 m (6600 ft). The latter spring cluster contains highly productive perennial springs and is discussed in greater detail later. These springs sustained moderate to high yields with variable flow durations.

Small sub-catchments (hectares) and minor slope concavities (100's to 1000's m²) often contain springs, spring clusters, and seeps at their distal ends. Ten springs occur within these landscape features (Springs 4, 6, 7, 8, 10, 40, 41, 47, and 63). Most had
low yields and short flow durations. Several springs had intermediate discharges but short flow duration.

Active channels contain seven springs (Springs 12, 13, 25, 36, 42, 60, and 62). All but one was discovered after stream discharge was very low. These springs are points or areas where local water tables intersect the channel. Consequently the location of these springheads did change. The remaining spring (Spring 42) was located at the upper end of an intermittent channel and was only noted once in June, 1991.

The interpretation of field mapping results and morphologic associations demonstrate that surficial, unconsolidated Quaternary materials and deposits do function as aquifers. Additional examination of the groundwater regime of the Maynard Creek catchment supports this interpretation.

Hydrograph Analyses

The hydrograph constructed from Williams' (1967) data was examined to interpret the character of the flow regime of Maynard Creek in 1966. The hydrograph displays two sharp peaks that represent a brief period of greatly increased streamflow (Figure 13, p.49). The peaks are generated primarily by rain and snowmelt runoff. Baseflow is sustained by delayed groundwater discharge from less conductive aquifers. Baseflow dropped to less than 28 lps (1 cfs), and was typically between 28 lps and 56 lps (2 cfs) during eight months of the year of record. Peak flows exceeded 650 lps (23 cfs). The majority of flow occurred during less than two months of the year (May and June). Shallow flow through conductive surficial materials may exist, but cannot be accurately differentiated by the interpretation of hydrograph data alone.

A flow duration curve can be used to assess the ability of a catchment to store groundwater (Figure 25). A steeply sloping duration curve is characteristic of a highly variable stream system, the flow of which is primarily sustained by direct surface runoff.
Figure 25. Flow duration curve for Maynard Creek stream discharge (Williams, 1967).
The low-flow end of the duration curve is flat if groundwater storage exists (Leopold, 1994). The initial steep slope of the flow duration curve for Maynard Creek indicates that groundwater storage is limited. The persistent low-flow of less than 20 lps suggests that contributing aquifers are either small, have low storage capacity and yield, or do not discharge into the catchment. Limited groundwater storage in isolated surficial Quaternary aquifers could produce such a hydrologic regime.

The stream hydrographs constructed for this investigation represent a short period of stream discharge from the south and north fork of Maynard Creek (Figure 18, p.54). The total volume of baseflow at these two measurement points is less than 7 lps (0.25 cfs), or about 12% to 25% of the baseflow of Maynard Creek, as measured by Williams (1967). Apparently, groundwater discharge to the streams below the two measurement points produces the remaining 75% to 88% of the baseflow. This requires that a groundwater discharge zone is located below the two measurement points (1976 m, 6520 ft, and 1909 m, 6300 ft) and above the Williams measurement point (1809 m, 5970 ft). This discharge zone exists within some of the thickest surficial deposits in the catchment.

Nineteen of the 62 springs (30%) exist between the measurement points and discharge directly from surficial materials. Eight of these springs had medium or high yields. Only three low yield bedrock fracture springs and one high yield bedrock spring (Spring 51) are located in the same measurement area (Plate 3, Figure 14, p. 50). A relatively high proportion of stream discharge in this measurement reach is maintained by springs and seeps discharging groundwater through surficial, unconsolidated Quaternary deposits. Little groundwater discharge to the surface appears to occur from bedrock related springs.
Spring Water Temperatures

Spring water temperatures are affected by meteorological events. This is demonstrated in the case of a prominent spring that flows from the base of a rock glacier (Spring 37). The spring thermograph in Figure 23 (p. 61) displays a steady increase in water temperature that coincides with an increase in mean daily air temperatures during the early summer months (Figure 17, p. 53). Two weeks prior to field observation on September 13, 1991, maximum air temperatures recorded at the Bozeman 12 NE Station (1805 m, 5920 ft) were high and ranged around 27°C (80°F), and low temperatures were around 10°C (50°F). The result was a peak of water temperature at Spring 37. The week immediately after this peak, high temperatures ranged about 10°C (50°F) with lows ranging between 0°C (32°F) and -10°C (14°F). Also, precipitation was over 2.5 cm (1 in) of water-equivalent. Temperature variability and total precipitation was likely to have been greater at the rock glacier (2273 m, 7500 ft). The result was a decrease in spring water temperature of about 0.8°C (1.4°F). The response of spring water temperature to changes in weather indicates that groundwater is stored in the rock glacier at shallow depths and not derived entirely from core-ice melting.

Other springs also respond to seasonal temperature variations. Figure 22 (p. 61) displays three spring water temperature regimes. Springs 23, 48, and 49 typify the response of many springs in the catchment to increased summer air temperatures. Springs 23, 48, and 49 all discharge directly from surficial, unconsolidated Quaternary deposits.

In general, springs in the Maynard Creek catchment are sensitive to air temperature variability. The springs in the catchment occur over a 606 m (2000 ft) elevation gradient. On the average, atmospheric temperature decreases at a nearly constant rate of 0.65°C (1.2°F) per 100 m (328 ft) (Neiburger and others, 1973). This rate is the normal lapse rate. The actual rate of cooling is called the environmental lapse rate, which varies between 0.5 and 1.0°C (0.9 and 1.8°F) per 100 m (328 ft) (Lutgens and Tarbuck, 1989). The
spring water temperatures, if sustained by shallow surficial aquifers, will be influenced by air temperature and the environmental lapse rate. Figure 26 is a correlation of spring water temperatures and elevation for a single day of observation. The R-squared value of the correlation coefficient for the best fit line is 0.495, which suggests a correlation between spring water temperature and elevation. The influence of elevation and air temperature explains approximately half of the total variance in spring water temperatures.

![Figure 26. Correlation of all spring water temperatures and elevation. The temperatures were recorded on June 19, 1991.](image)

The temperature gradient inferred from the line of best fit for the data is $1^\circ$C (1.8°F) per 121 m (399 ft), or about $0.8^\circ$C (1.4°F) per 100 m (328 ft). The temperature gradient determined for all springs fits within the general range of environmental lapse rates. If spring water temperature changes mimic air temperature changes, the aquifers that sustain spring flows must be shallow and surficial in nature.
Spring water temperatures taken on one day for the 23 most persistent springs also display a correlation with elevation (Figure 27). The R-squared value of the correlation coefficient for the best fit line is 0.759. A correlation between elevation and the fourteen springs that persisted during five consecutive observations was analyzed, and the R-squared value was 0.745. The strong correlation of persistent spring temperature with elevation and air temperature is apparent. Approximately three-quarters of the total variance is explained by the change in air temperature with changes in elevation when only the most persistent springs are considered.

\[ y = 2496.4 - 109.82x \quad R^2 = 0.759 \]

Figure 27. Correlation of spring water temperature and elevation. Temperatures of 23 springs that persisted through July 28, 1991.
The temperature gradient displayed in persistent springs is 1°C (1.8°F) per 83 m (274 ft) or 1.2°C (2.2°F) per 100 m. This rate of cooling is similar to the normal and environmental lapse rates. The average of the two measured temperature gradients is 1°C (1.8°F) per 102 m (335 ft), which is similar to the theoretical dry adiabatic lapse rate of 1°C (1.8°F) per 100 m (328 ft), and within the known range of environmental lapse rates. The correlations of spring discharge temperature and elevation indicate that water stored in geologic materials in the catchment are affected by mean daily air temperature as it varies with elevation. The correlation is greatest for persistent springs. This indicates that aquifers sustaining persistent springs are shallow and surficial.

Spring water temperatures also are affected by mean daily air temperature throughout the year. This is evident if one compares the thermograph of the Deer Park spring (Spring 23) to the graph of mean daily air temperature taken at the Bozeman 12 NE Station during the period of investigation. The peak temperature of spring water lags behind that of the atmosphere by approximately 60 days (Figure 28).

The water temperature is depressed immediately following persistent warming periods that raise mean daily air temperatures well above freezing. The first water temperature measured was day 202 (April 20, 1991), which immediately proceeded eight consecutive days when the mean daily air temperature increased from -3 to 12°C (27 to 54°F). Spring water temperature was lowered at least 1.0°C (1.8°F). A similar depression in water temperature occurred around day 550. The mean daily air temperature increased from -2 to 8°C (28 to 46°F) in eleven consecutive days of warming weather. Spring water temperature was depressed at least 0.1°C (0.2°F). The two warming periods initiated sufficient localized snowmelt runoff waters to influence spring water temperature. The significance of sustained snowmelt runoff on spring discharge and water temperature is better defined by a comparison of annual snowpack measurements and spring water characteristics.
Figure 28. The mean daily air temperature at the Bozeman 12 NE Station (1805 m, 5920 ft) and spring water temperature of the Deer Park spring (Spring 23) (2012 m, 6600 ft).

Discharge volume and water temperature of the Deer Park spring (Spring 23) was closely monitored during the snowmelt runoff period. The spring water characteristics are influenced by snowmelt runoff waters. Figure 29 represents this relationship between snowmelt runoff, which occurs as snowpack rapidly diminishes, and spring discharge. The dramatic increase in spring discharge is a direct result of the loss of snowpack and increase in water available for aquifer recharge. The initial slight increase in spring water yield is the result of recharge from localized snowmelt runoff which does not coincide exactly with the reduction of snowpack at the SNOTEL site. Many springs, especially the
Deer Park spring, are sustained by shallow, surficial aquifers that recharge quickly following snowmelt and precipitation events. The temperature of Deer Park spring water is also affected by snowmelt water recharge (Figure 30). The temperature of the spring water is depressed by rapid influx of cold snowmelt waters. This quickly reduces the spring discharge temperature by as much as 1°C (1.8°F). The peak discharge of Spring 23 is sustained by rapid snowmelt recharge and quick flow through the contributing aquifer. The Bridger springs have a similar but delayed temperature response to snowmelt recharge (Figure 22, p. 61). This rapid temperature and discharge change is only possible if the aquifers are surficial, unconsolidated, and close to the recharge area.

Figure 29. Snow-water equivalent at the Maynard Creek SNOTEL Station (2170 m, 7160 ft) and discharge from the Deer Park Spring 23 (2006 m, 6580 ft).
Figure 30. Temperature and discharge of the Deer Park spring (Spring 23).

The influence of snowmelt runoff on spring water discharge and temperature identifies several characteristics of the contributing aquifer. First, the recharge area is very close to the discharge area. Second, the hydraulic conductivity of part of the aquifer is high. These characteristics are evidenced by the brief lag time between the initiation of snowmelt runoff and peak spring discharge and depressed water temperature. The coincidence of increased discharge and depressed temperature indicates complete flow of water through the aquifer and not a flush of "piston-type flow" (Campbell and others, 1995) of shallow groundwater stored from the previous year's runoff. Also, the contributing aquifer sustains significant delayed yields. This suggests that the aquifer has a useful storage capacity and low to intermediate values of hydraulic conductivity and storativity. The best explanation of the characteristics of the spring hydrograph is that discharge is sustained by storage in an aquifer composed of at least two different materials.
The interpretation of mapping results, stream and spring hydrographs, meteorologic and snow-survey data, and spring water characteristics demonstrates that surficial, unconsolidated Quaternary deposits form shallow aquifers that sustain springs and seeps in the Maynard Creek catchment. In many cases this can be deduced from field mapping and site interpretations. Empirical data collected during spring monitoring also confirms the existence of the surficial aquifers.

**Surficial Quaternary Aquifers and Bedrock Aquifers**

Groundwater stored in surficial, unconsolidated Quaternary aquifers can be distinguished from groundwater stored in bedrock aquifers. This is best demonstrated with field interpretations, water chemistry, and spring water monitoring.

**Field Interpretations**

As previously discussed, site inspection of many springs confirms the existence of spring discharge points in bedrock and surficial deposits. Mapping interpretations were used to distinguish site characteristics unique to surficial aquifers. These aquifers lie immediately upslope of prominent spring clusters. This is typified by the spring clusters in glacial outwash deposits located at 2000 m (6600 ft) and 1976 m (6520 ft) in main valley bottoms of the catchment (Plate 3). Bedrock aquifers are inferred where springs discharge from bedrock outcrops. This arrangement is apparent at 1918 m (6330 ft) where Spring 51 discharges from a fractured Sedan formation welded tuff outcrop. No other high volume springs are obviously associated with bedrock. These field observations constitute ocular evidence that distinguishes bedrock and surficial aquifers.
Chemical Interpretaions

Chemical analyses of water samples were used to distinguish groundwater sources. The specific electrical conductance (SC) of all spring waters was not monitored but sampled only once during this investigation. All values of SC were low in June. Sampling groundwater at this time, during maximum groundwater recharge, may affect the results in two ways. Groundwater and soil water residence times are short, and mixing of surface water and groundwater is likely.

The results of previous work on the waters of glacio-fluvial systems in the European Alps, Alaska, and Baffin Island were compared to the results of this investigation. The SC of all of the springs in Maynard Creek ranged between 0.16 and 0.50 mS. The results of Fenn (1987) indicate that proglacial streams in Switzerland have SC values that range between 0.13 and 0.32 mS. Slatt (1970) found proglacial streams in Alaska have SC values between 0.04 and 0.32 mS. Church (1974) found proglacial streams in Baffin Island have a SC between 0.01 and 0.62 mS.

Oerter and others (1980), and Behrens and others (1971) demonstrated that the SC of supraglacial waters in Switzerland range between <0.01 and 0.02 mS. Rainwater in the western United States has a range of SC values from <0.002 to 0.042 mS (Feth and others, 1964). Surface waters and groundwaters can have SC as low as 0.05 mS (Hem, 1989). Spring waters in the Maynard Creek catchment have SC values similar to those found in proglacial streams. Spring waters studied during this investigation have low ionic concentrations and short residence time in their contributing aquifers. These aquifers, regardless of material type, must be shallow and have high values of hydraulic conductivity. The value of SC measurements alone is limited for determination of groundwater storage sources.

Water samples were collected from the Maynard Creek catchment by numerous individuals over a period of two decades. Collection methods and laboratory procedures
are known only for the two samples taken during this investigation. The cation-anion ratio was used to check the accuracy of all analytical results (Fetter, 1980, Domenico and Schwartz, 1990). Analytical values for substances reported as less than (<) a detectable threshold do not represent any specific amount of the substance and were not included in the ionic balance totals (Hem, 1989). Results reported as "Tr", or trace, were not included for the same reason. Creek water analyses that reported only one or two measurable substances (C1, C2a, C3, and C4) were not balanced. Results with a cation-anion ratio of ± 10 percent were used for interpretation (Table 9).

The most accurate analyses have been used to construct a Piper diagram (Figure 31) that represents the composition of waters with respect to both cations and anions (Piper, 1944, Hem, 1989). The trilinear diagram portrays the chemical character of samples taken from wells developed in bedrock, from streams, and from springs. All wells were completed in the Livingston Group. Stream water samples were taken from both Maynard Creek and Bridger Creek. Spring water samples were taken from springs that flow from surficial, unconsolidated Quaternary deposits.

Water analyses plotted on the Piper diagram can be used to discriminate between distinct water types (Piper, 1944, Morris and others, 1983). All water analyses indicate that weak acids exceed strong acids with bicarbonate as the dominant anion. Sodium is the dominant cation in well water. Spring water has calcium as the dominant cation. Cation dominance in stream water is not clearly defined by two sample points.

Plotting of analyses in the diamond-shaped field indicates a close similarity in the composition of spring and stream waters. These waters are calcium and bicarbonate enriched. This water type has carbonate hardness (secondary alkalinity) of greater than 50 percent. The arrangement of well water data points indicates that these waters have variable composition and tend to have carbonate alkalinity (primary alkalinity) of about 50 percent (Morris and others, 1983).
<table>
<thead>
<tr>
<th>Source</th>
<th>Cations (meq/l)</th>
<th>Anions (meq/l)</th>
<th>Cations:Anions</th>
</tr>
</thead>
<tbody>
<tr>
<td>W1a</td>
<td>2.11</td>
<td>1.94</td>
<td>1.09*</td>
</tr>
<tr>
<td>W1b</td>
<td>3.75</td>
<td>2.59</td>
<td>1.45</td>
</tr>
<tr>
<td>W1c</td>
<td>3.97</td>
<td>2.00</td>
<td>1.99</td>
</tr>
<tr>
<td>W1d</td>
<td>1.11</td>
<td>1.39</td>
<td>0.80</td>
</tr>
<tr>
<td>W1e</td>
<td>1.07</td>
<td>1.27</td>
<td>0.84</td>
</tr>
<tr>
<td>W1f</td>
<td>1.27</td>
<td>1.29</td>
<td>0.98*</td>
</tr>
<tr>
<td>W2</td>
<td>0.99</td>
<td>1.25</td>
<td>0.79</td>
</tr>
<tr>
<td>W3</td>
<td>2.45</td>
<td>2.42</td>
<td>1.01*</td>
</tr>
<tr>
<td>W4</td>
<td>2.17</td>
<td>2.18</td>
<td>1.00*</td>
</tr>
<tr>
<td>S1</td>
<td>0.97</td>
<td>1.10</td>
<td>0.88</td>
</tr>
<tr>
<td>S2</td>
<td>3.99</td>
<td>3.91</td>
<td>1.02*</td>
</tr>
<tr>
<td>S3</td>
<td>4.81</td>
<td>4.85</td>
<td>0.99*</td>
</tr>
<tr>
<td>C2b</td>
<td>2.43</td>
<td>2.50</td>
<td>0.97*</td>
</tr>
<tr>
<td>C5</td>
<td>4.01</td>
<td>4.05</td>
<td>0.99*</td>
</tr>
<tr>
<td>C6</td>
<td>1.06</td>
<td>3.91</td>
<td>0.28</td>
</tr>
<tr>
<td>SS1</td>
<td>4.06</td>
<td>3.90</td>
<td>1.04*</td>
</tr>
<tr>
<td>SS2</td>
<td>3.96</td>
<td>3.93</td>
<td>1.01*</td>
</tr>
</tbody>
</table>

* Indicates analyses that have an accuracy of ± 10 percent.
A nearly straight line between data points in all three fields is evident in Figure 32. This may indicate a binary mixing system with surficial and bedrock aquifer waters, a change in hydrochemical facies of water as it migrates down a hydraulic gradient, or separate and unique chemical reactions within isolated aquifers (Cheng, 1988). Identification of processes which control the hydrogeochemistry of all waters in the Maynard Creek catchment is beyond the scope of this investigation, but the chemical
composition of spring yields are similar to that of streams, and plot closely on the Piper diagram, while bedrock aquifer yields form a separate linear pattern. The linear pattern of bedrock yields is sufficiently distinct from the tightly clustered pattern of surficial spring yields to distinguish surficial aquifer discharge from bedrock aquifer discharge.

**Spring Water Monitoring Interpretations**

Spring discharge monitoring produced results that distinguish surficial Quaternary aquifer waters and bedrock aquifer waters. A rapid decline in spring discharge immediately following a recharge event is a characteristic of small, shallow, unconsolidated aquifers (Valdiya and Bartarya, 1991). All springs in this investigation had yields that steadily decreased through the summer and fall months of 1990 and 1991. Greatly increased discharge during and immediately after snowmelt runoff events occurs in several springs. Of the original 62 springs, only 14 sustained flow through five consecutive observations (about 3 months). Thirteen of these 14 persistent springs discharged directly from surficial Quaternary deposits. Only springs 23, 48, and 49, each of which discharge from surficial deposits, were known to persistent through 1990 and 1991. The recorded baseflow from the catchment is between 28 and 56 lps (1 and 2 cfs) (Williams, 1967). About 12% to 25% of this baseflow is accounted for by these three springs that initiate perennial stream flow on the north and south forks of Maynard Creek. This indicates that shallow, surficial materials form storage systems that discharge into the catchment. The remaining bedrock related spring (Spring 51) did not sustain flow through the winter of 1991-92. This suggests that even persistent springs sustained by bedrock aquifers are shallow and have low storage capacities.

Very shallow, unconfined aquifers are affected by air temperature changes (Fritz and others, 1990). The temperature regime of many spring waters in the study area respond to atmospheric influences. Water migrating toward springs from deep sources is unlikely to
register large temperature differences through time (Fritz and others, 1990). Groundwater derived from deep sources display nearly constant temperatures (Moore, 1984). Seasonally variable spring temperature regimes are typified in Figure 32 with Springs 23, 48, and 49. These are high yield springs and the only known perennial springs in the catchment. They are sustained by surficial Quaternary aquifers.

![Temperature regime of springs sustained by bedrock aquifer storage (Springs 51 and 53) and surficial Quaternary aquifer storage (Springs 23, 48, and 49).](image)

Two persistent springs (Spring 51 and 53) maintain nearly constant elevated temperatures. Spring 51 is physically associated with a large and continuous bedrock outcrop. This spring maintained high yields (>1.26 lps, 20 gpm) but was not perennial. Spring 51 is sustained by shallow water storage in fractured bedrock. The initial lower temperature of this spring is due to the influence of cooler recharge waters. The depth of
storage is sufficient to buffer the influence of seasonal air temperature variations, but not snowmelt runoff recharge events.

Spring 53 exists in a narrow outwash deposit that overlies the mudstone member of the Sedan formation. The spring area was modified during development, and the arrangement of the water collection and distribution system was not determined. Nearly constant and elevated spring water temperature indicates that the spring is sustained by bedrock aquifer storage.

The water temperature of Spring 53 is slightly reduced one to two months after the temperature reduction experienced by springs 23, 48, and 49. This temperature fluctuation may be related to snowmelt runoff recharge or seasonal air temperature changes. In either case, the aquifer is probably shallow with limited storage in fractured bedrock and regolith.

In this study, twenty-one of the twenty-three most persistent springs are thought to be sustained by surficial, unconsolidated Quaternary aquifers. These springs display an average temperature fluctuation of 1.9°C (3.4°F). Springs 51 and 53 are sustained by bedrock aquifers, and their average temperature fluctuation is 0.2°C (0.4°F). Those springs that are sustained by surficial aquifers tend to have low winter temperatures, typically between 2.0°C (36°F) and 4.0°C (39°F), that increase to near the temperature of the bedrock aquifer waters. Bedrock water temperatures are initially higher (about 5.0°C, 41°F) and were maintained throughout the period of observation. These differences in water temperatures enables bedrock aquifer water (Spring 51 and 53) to be distinguished from surficial, unconsolidated Quaternary aquifer water (Spring 23, 48, 49).
Characterization of Surficial, Unconsolidated Quaternary Aquifers

Site interpretations, seismic refraction interpretations, and generalized schematic models are used to characterize the surficial, unconsolidated Quaternary aquifers identified in this investigation. Also, a range of porosity, storativity, and hydraulic conductivity values are estimated for the Quaternary materials.

Quaternary Deposits that Do Not Function as Aquifers

Some of the springs and seeps located in the catchment are not sustained by groundwater discharge. In general, these are springs and seeps that have low yields and very short flow durations. Many of the discharge points are associated with soil water storage. Evidence of this includes observations of point discharge from broad areas of saturated soil, flow through deep soil fractures and soil pipes, and point discharge from animal burrow networks. Animal burrows are known to concentrate soil water flow at specific locations in the catchment (Grady and others, 1982). Figure 33 depicts the soil water runoff processes observed in the catchment.

Talus deposits display variable thicknesses over large portions of the upper catchment. The maximum thickness observed was approximately 5 m (16.5 ft). A few broad seep areas and minor springs emit from the base of these deposits. Their flow ceases shortly after snowpack disappears. Talus deposits are hardened, stable, and covered by a thin veneer of loose surface rubble. The silty matrix is partially cemented with CaCO₃. Active ephemeral channels incised on the talus surfaces indicate frequent surface water runoff. No evidence of water-bearing layers or stratified slope deposits (grezes) was noted during mapping. The closed clast-supported fabric has resulted from the filling of voids by washing of fines into the original open-work fabric (Selby, 1982). Weathering of talus...
slopes also reduces macropore space within the deposits. "Only about 12% of the original sediment needs to be broken down to fines for the macropores to become completely filled, with a consequent decrease in hydraulic conductivity of several orders of magnitude" (Statham and Francis, 1986). The few springs that discharge from talus have low discharge and short duration, and are located below late-season snowpatches and coarse deposits. In general, talus deposits do not function as aquifers because of their low permeability and low hydraulic conductivity. They do promote overland flow to surficial recharge areas located lower in the catchment.

Figure 33. Soil water discharge model.

Mass wasting deposits, as classified by Varnes (1978), are often associated with groundwater discharge in the Maynard Creek catchment. Many failures occur within pre-existing surficial deposits, and were initiated by high groundwater levels or high soil water
content. Failure surfaces and deposits are often saturated for weeks or months. Rock, debris, and earthen mass wasting deposits have a wide range of hydrogeologic characteristics and cannot be easily categorized. These deposits have a character that is similar to the host material in which the failure occurred.

In most cases, mass wasting deposits in the catchment are small and isolated units. The one large deposit at the bottom of the catchment is thin (<4 m, 13.2 ft), highly anisotropic, and contains local zones of increased hydraulic conductivity (Schafer and Associates, 1990). No springs or seeps were located in this deposit. In general, springs and seeps associated with mass wasting deposits sustain short to medium flow durations and low yields. The mass wasting deposits are not individual aquifers, but are minor components of larger surficial aquifers.

The modern alluvial deposits mapped during this investigation have very limited areal extent and minimal thicknesses. Most stream channels are formed within other Quaternary deposits, particularly undifferentiated till and outwash, and display only a very thin veneer of mobile sediment. The amount of water stored in the small lacustrine sub-catchment is unknown, but the stream reach below it sustains only intermittent and discontinuous flow. This would indicate low storage volumes or storage loss to bedrock aquifers. Alluvial materials in the catchment have hydrogeologic characteristics of aquifer materials, but provide very little storage volume and do not function as independent aquifers.

**Glacial Deposits as Aquifers**

Glacial deposits are extensive throughout the study area, and have maximum observed thicknesses of 20 m (66 ft). The physical and hydrogeologic character of these deposits is highly variable. The rock glacier forms a unique and isolated Quaternary aquifer. Glacial outwash deposits and undifferentiated tills form small, localized aquifers.
that have distinctive characteristics. The mass of undifferentiated till that covers much of the catchment also functions as an aquifer system.

The rock glacier, located at 2242 m (7400 ft) in the northwest portion of the catchment, functions as a shallow Quaternary aquifer (Figure 34). Other authors have discovered "stream portals" that discharge from well-defined and stable points at the base of rock glacier fronts (Jackson and McDonald, 1980; Haeberli, 1985). Two stream portals (springs) exist at the toe of the Maynard Creek rock glacier moraine. Discharge volumes from rock glaciers are less than that for glaciers of similar size, but the diurnal flow variability is less than that for glacial streams (Gardner and Bajewsky, 1987). Haeberli (1985) estimated yields of between 2 lps (0.07 cfs) and 50 lps (1.8 cfs) from a medium sized rock glacier with length of 1000 m (3280 ft). The rock glacier in this study is 400 m (1312 ft) in length with summer yields from two stable points of about 2 lps (0.07 cfs).
Flow rates within rock glaciers of $10^1$ and $10^2$ m/d were determined with tracers by previous investigators (Johnson, 1981; Evin and Assier, 1983). The throughflow velocities experienced in rock glaciers produce a lag time between air temperature change and intense rainfall, and the effects on rock glacier discharge (Gardner and Bajewsky, 1986). Johnson (1981) found that the most significant fluctuations in discharge from rock glaciers resulted from rainfall events. A lag time did occur when cold precipitation depressed the water temperature of Spring 37.

Glacial outwash forms distinct fans or chaotic deposits at three main areas in the catchment (Plate 2). The deposits are known to be at least 4 m (13.2 ft) thick. Groundwater, streamflow, and surface infiltration recharge the coarse and porous deposits. A hydraulic discontinuity is encountered at the bedrock contact and water surfaces at the base of the deposits (Figure 35). The volume of each deposit is small, and groundwater storage capacities are limited. The glacial outwash deposits grade into adjacent tills and have the volume and material characteristics needed to function as important components of surficial aquifers. The glacial outwash deposit at 2012 m (6600 ft) in the southern part of the catchment was studied to characterize a surficial, unconsolidated Quaternary aquifer.

Figure 35. Glacial outwash and undifferentiated till aquifer model.
Undifferentiated tills are known to function as significant aquifers (Kattleman, 1989, Driscoll, 1986, Jamieson and Freeze, 1983). Till stores useful quantities of water, but releases it slowly over long periods of time (Catt, 1988). These deposits were observed to be between 1 to 20 m (3 to 66 ft) thick and cover over 60% of the Maynard Creek catchment. The matrix of the tills are clayey and rock content is high. Laterally discontinuous zones of cobble-boulder supported tills with coarse matrix lie within the predominantly clayey tills (Figure 11, p. 48). The till deposits grade into and interbed with outwash. Also, the tills display a wide ranges of textures which result in variable hydrogeologic properties. Undifferentiated tills and glacial outwash function as the main components of small and isolated aquifers within sub-catchments (Figure 35, p. 89).

The variably thick blanket of undifferentiated till that covers much of the catchment also functions as an aquifer. The larger, catchment-sized aquifer is poorly defined and contains small but productive, isolated aquifers. The proportion of groundwater discharge to the surface from the larger, catchment-sized till aquifer and that from small, isolated aquifers is unknown.

The observation that stream discharge increases between measurement points that are located in thick till indicates that groundwater is discharging from the blanket of till to the stream network (Figure 36). The continuous till blanket is known to be heterogeneous and anisotropic. Perennial stream reaches only exist where thick till contains channels that lie below the permanent watertable. The migrating spring discharge points observed at a few locations sustain intermittent streamflows. This occurs where channels intersect seasonally high watertables. Undifferentiated tills maintain a large percentage of Maynard Creek baseflow between 28 to 56 lps (1 to 2 cfs). This is equivalent to an annual yield of less than $9.0 \times 10^5$ to $1.8 \times 10^6$ m$^3$/year (730 to 1460 acft/yr), or less than 10% to 20% of the annual flow.
Bridger Aquifer

The Bridger spring cluster area (1918 m, 6330 ft) contains several intermittent and perennial high yield springs, but no large seeps (Figure 4, p.39, Plate 3). The surficial deposits that store groundwater and sustain these spring discharges form the Bridger aquifer. The aquifer maintains perennial flow of the north fork of Maynard Creek.

The Bridger aquifer exists in thick glacial deposits where younger glacial and fluvial processes have buried and dissected the older depositional features. At this location, a relic, moraine-parallel, glacial meltwater channel (a fosse) parallels an older medial moraine. The aquifer contains modern and glacial channel networks and small dump moraines (Souchez and Lorrain, 1987) that deposited outwash, fluvium, and coarse-grained supraglacial diamictites (Eyles, 1983). These highly conductive deposits are contained within undifferentiated till and were altered and buried by more recent Quaternary processes and ski area construction.
The two most productive springs (Springs 48, 49) are perennial, but lesser springs (Springs 50, 51, 58, 62) also discharge from the aquifer. Spring 49 was developed for residential water supply during this investigation. Spring 51 was developed many decades ago for the same purpose. Springs 48 and 49 lie immediately below an 80 m (265 ft) long linear depression. They discharge from recessed concavities that had advanced upslope along the trace of the linear depression by sapping (Higgins, 1984).

Drilling into the linear depression intersected saturated, unconsolidated materials at shallow depths (<2 m). The channel-like depression is immediately down-gradient and connected to the fosse. Excavation of one springhead (Spring 49) revealed sorted, clean gravels and small cobbles that were concentrated in a concave lense and buried by undifferentiated till. The material in the lense is a fluvial deposit. Two percolation tests were completed in an adjacent undifferentiated till deposit and the unsaturated hydraulic conductivity was determined to be 0.35 to 0.40 m/d (1.2 to 1.3 ft/d). The buried channel deposit examined during development of Spring 49 was predominantly coarse gravels and small cobbles with an expected saturated hydraulic conductivity of $10^2$ to $10^4$ m/d.

Spring 58 discharged through undifferentiated till from a steep undercut bank at a point 4 to 5 m (13 to 17 ft) above Maynard Creek. Flow persisted through a minor zone of high hydraulic conductivity. This discharge point occurs where a minor buried channel is exposed, and perched groundwater flows to the surface above the water table elevation.

Spring 51 discharged from a fractured bedrock aquifer. The discharge point existed several meters above Maynard Creek, but flow was not perennial. The bedrock aquifer that sustained this flow is physically separated from the surficial, unconsolidated Quaternary deposits that form the Bridger aquifer.

Seismic refraction methods were used to identify subsurface features in the Bridger aquifer area (Figure 4, p.39). Two seismic lines (Lines 18 and 22) were positioned to intersect the channel-like depression above Springs 48 and 49. The first arrival data was
complex and not clearly interpretable. No obvious buried channel(s) were detected, but the material containing Springs 48 and 49 is dense, clayey till which overlies shale or weathered sandstone. The contact between the two materials has irregular bedrock high-points, contains numerous small channels, or contains large boulders (>1m, 3.3 ft).

Partially buried boulders exposed at the surface and drilling difficulties indicate that large buried boulders are present beneath Lines 18 and 22.

The time-distance diagram of Line 14 indicates that deeply weathered younger undifferentiated till covers weathered sandstone or mudstone (Figure 37). Also, a low

Figure 37. Schematic interpretation of seismic Line 14.
velocity zone exists at the till-bedrock contact. This subsurface low velocity zone represents a buried channel. The buried channel lies within a large slope concavity and is connected to an ephemeral channel and low-yield spring (Spring 50). The entire area has been modified for ski run construction.

Seismic Line 17 crosses nearly perpendicular to the strike of an outcrop of Sedan welded tuff. The time-distance diagram represents a bedrock aquifer that underlies forest soil and older till (Figure 38). Spring 51 discharges from this shallow bedrock aquifer.

![Figure 38. Schematic interpretation of seismic Line 17.](image-url)
The Bridger aquifer discharge area exists where groundwater concentrates through buried channels and undifferentiated tills. Coarse, clast-supported till, thought to be outwash deposits and dump moraine deposits, were found within the clayey undifferentiated till. These deposits comprise a small proportion of the total aquifer volume, but are important components of the Bridger aquifer. The buried channels are highly conductive and spatially extensive, but have low storage volumes. The extensive undifferentiated tills have low conductivities, high storage volumes, and sustains low but prolonged yields. These glacial deposits form an aquifer system that maintains perennial spring flows, contributes to peak stream flows, and sustains baseflow of the north fork of Maynard Creek.

Deer Park Aquifer

The Deer Park spring cluster contains several prominent springs and many large seeps (Figure 5, p.39, Plate 3). The surficial deposits that store groundwater that sustain the cluster, form the Deer Park aquifer. Spring 23, the primary water source of the Deer Park day lodge, and the perennial flow of the main (south) fork of Maynard Creek, are both sustained by the Deer Park aquifer.

The surficial deposits that form the Deer Park aquifer are contained and isolated within the "South Bowl" sub-catchment. The aquifer is a well-defined and discrete unit, and thicknesses of the Quaternary deposits can be approximated (Figure 39). A generalized cross-section through the aquifer depicts the arrangement of Quaternary materials and bedrock formations, and includes the approximate values of storativity, hydraulic conductivity, and discharge (Figure 40).

The discharge zone of the Deer Park aquifer is located where abundant phreatophytic vegetation, persistent large seeps, and numerous intermittent and perennial high yield springs occur. Structures, buried utilities, and landscaped ski runs exist on the lower
Figure 39. The extent and approximate thickness of the Deer Park aquifer.

Figure 40. Cross-section of the Deer Park aquifer including approximate values of storativity (S) in percent, hydraulic conductivity (K) in m/d, and baseflow discharge (Qb) in lps.
aquifer surface. These facilities lie on glacial outwash that may have formed a distinct deposit prior to slope disturbances.

The upper part of the aquifer consists of moraine-like till deposits. These till deposits grade into the surrounding outwash, mass wasting, and talus deposits. Interbedding of the surficial deposits is likely. The aquifer surface is dissected by modern and relic channels. Ephemeral channels and erosional features have been modified by ski run construction.

The Deer Park aquifer is complex. Spring 22 discharges from within the confines of abandoned channel levees located at the base of the outwash deposit (Figure 5, p. 39). Spring 23 flows from the base of the outwash deposit where it overlies the Telegraph Creek formation. The response of Spring 23 discharge to snowmelt recharge (Figure 29, p. 75) is very rapid and peaks within several days. Lloyd (1983) conducted investigations of spring flows from glacial materials. The results are represented by two generalized spring hydrographs which depict discharge from sand and gravel glacial deposits and from boulder clay glacial deposits (Figure 41). The hydrograph of Spring 23 (Figure 20, p. 59) has characteristics of a sand and gravel aquifer and a boulder clay aquifer. Initial response (rising limb of the hydrograph) to recharge is similar to that produced by sand and gravel aquifers. The falling limb of the hydrograph is similar to that produced by boulder clay aquifers. This indicates that the Deer Park aquifer is composed of at least two materials, each having unique physical and hydrogeologic characteristics.

Seismic refraction was used to characterize geologic materials and identify subsurface features located in the Deer Park aquifer discharge zone (Figure 5, p. 39). Line 19 was placed immediately up gradient from the catchment's most productive spring (Spring 23). The time-distance diagram for Line 19 represents modified and weathered glacial outwash that overlies the Telegraph Creek sandstone and shale (Figure 42). A low velocity zone exists in the middle of the line. This low velocity zone is interpreted to be a buried channel. The seismic line is perpendicular to a buried channel that connects with Spring 23.
The coincidence of reduced seismic velocities, which are detected at the same location by forward and reverse shooting, indicate that less dense geologic materials or a narrow depression exists at that location. No direct evidence was found to confirm that a buried alluvial deposit is located beneath line 19, although such a deposit was inspected at the Bridger groundwater discharge area. However, partially buried and modified channel segments, and relic channel levees do exist near seismic line 19. This evidence, in conjunction with the seismic velocity profile, supports the interpretation that a buried channel does exist and connects with Spring 23.
Seismic Line 3 is 100 m (330 ft) upslope from and parallel to Line 19 (Figure 5, p. 39). The time-distance diagram for Line 3 defines a sequence of surficial deposits that overlies the Telegraph Creek sandstone and shale (Figure 43). Modified and weathered outwash covers younger till. The diagram also depicts a low velocity zone. This indicates that a buried channel exists within the subsurface. The channel is at the base of a buried bedrock slope.
Interpretation of the time-distance relationship for seismic Line 4 is shown in Figure 44. The sequence of deposits includes weathered and modified outwash, older undifferentiated till, and Colorado sandstone. A subsurface low velocity zone indicates the presence of a buried channel which is located at the base of a buried bedrock slope. This
channel may be continuous beneath Lines 2, 3, 4, 7, and 19, but the time-distance diagrams of Lines 2 and 7 did not support this interpretation. The time-distance relationship of Line 2 and Line 7 both display a two-layer arrangement of modified outwash till over sandstone or shale bedrock. The interpretation is that the channel is discontinuous and contains older alluvial deposits and glacial deposits. Younger glacial outwash and till covers the channelized area. Later, the fan was modified by ski area development.

The aquifer system that maintains flow in the Deer Park spring cluster is composed of undifferentiated till, glacial outwash, and a buried channel network. The subsurface channels are subglacial and/or proglacial stream channels that were buried by undifferentiated till and outwash. The channels may have formed at the ice-rock interface as conduits within the glacial ice (R-channels) or as channels carved in bedrock at the glacier bed (N-channels) (Souchez and Lorrain, 1987). The N-channels, once formed, are more permanent and favor continued use by meltwater long after glacial retreat. These channels tend to promote coarse sediment deposition, as finer materials are transported by meltwaters (Souchez and Lorrain, 1987). The Deer Park aquifer channels have characteristics of the N-channels.

The glacial outwash consists of poor to well sorted sands, gravels, and cobbles. Buried channel deposits probably contain alluvium. The outwash and channel materials have high values of porosity, storativity, and hydraulic conductivity. The groundwater storage in outwash is greater than in buried channel deposits because it is thicker and more extensive. The buried channels form a discontinuous network that transmits groundwater to surface discharge zones.

Baseflow of the Deer Park springs is sustained by storage and delayed discharge from less conductive materials; in this case the undifferentiated tills that are so pervasive in
the upper catchment. The mass wasting deposits that border this aquifer system have similar matrix texture and rock content as the undifferentiated tills, but are much thinner and less extensive. Therefore, the mass wasting deposits do not contribute a significant amount of groundwater to the system. Talus deposits do not appear to store water, but shed runoff onto the unconsolidated aquifer recharge areas.

Figure 44. Schematic interpretation of seismic Line 4.
The porosity, storativity, and hydraulic conductivity of Quaternary deposits inspected during this investigation are approximated in Table 10. These approximations are derived from the empirically determined values established by other investigators (Table 1, p. 38).

<table>
<thead>
<tr>
<th>Material Type</th>
<th>Porosity (%)</th>
<th>Storativity (%)</th>
<th>Hydraulic Conductivity (m/d)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Talus</td>
<td>20-30</td>
<td>5-10</td>
<td>$10^{-4} - 10^{-2}$</td>
</tr>
<tr>
<td>Mass Wasting</td>
<td>40-50</td>
<td>5-10</td>
<td>$10^{-4} - 10^{-1}$</td>
</tr>
<tr>
<td>Modern Alluvium</td>
<td>25-40</td>
<td>20-30</td>
<td>$10^{2} - 10^{4}$</td>
</tr>
<tr>
<td>Till</td>
<td>30-50</td>
<td>5-20</td>
<td>$10^{-4} - 10^{1}$</td>
</tr>
<tr>
<td>Outwash</td>
<td>30-40</td>
<td>20-30</td>
<td>$10^{1} - 10^{2}$</td>
</tr>
<tr>
<td>Older Alluvium</td>
<td>25-35</td>
<td>20-30</td>
<td>$10^{1} - 10^{3}$</td>
</tr>
</tbody>
</table>

Groundwater Development

A discussion of groundwater development potential from surficial, unconsolidated Quaternary aquifers is constrained by available data. Many characteristics of the shallow groundwater regime within the Maynard Creek catchment have not been defined by this investigation. These include but are not limited to: 1) a complete water budget; 2) the percentage of groundwater storage that discharges to the surface within the catchment; 3) the connectedness of isolated, sub-catchment surficial aquifers with the larger, catchment-sized surficial aquifer; 4) the percentage of stream flow sustained by surficial aquifer
discharge; 5) groundwater storage in buried closed depressions; and 6) the exchange of groundwater between surficial aquifers and bedrock units. Recognizing these important undetermined factors, first approximations of the groundwater development potential from surficial aquifers can be estimated.

The surficial, unconsolidated Quaternary aquifers have limited development potential. Groundwater is concentrated in the Bridger and Deer Park aquifer areas where individual spring discharges range from 0.1 lps (0.004 cfs) to over 20 lps (0.7 cfs). Each isolated aquifer has an area of about 20 to 30 hectares (50 to 75 ac) with observed thicknesses between 1 and 20 m (3 to 66 ft). If the average thickness of each aquifer is assumed to be 15 m (49 ft), then the volume of each aquifer is less than $5 \times 10^6$ m$^3$ ($5 \times 10^3$ acft). The maximum and minimum thickness of the saturated aquifer materials, as defined by the height of the seasonal and permanent water table, is unknown for the two aquifers. Assuming the average saturated material thickness is half of the average aquifer thickness, or 8 m (26 ft), then the average aquifer storage volume for each aquifer is about $3 \times 10^6$ m$^3$ ($3 \times 10^3$ acft). If the porosity of the aquifer is 30%, then the aquifer storage volume of each aquifer is reduced to about $10^6$ m$^3$ ($10^3$ acft). If the average value of storativity is between that of outwash and undifferentiated till, or about 10%, then the amount of groundwater released from storage under the influence of gravity from each aquifer is about $10^5$ m$^3$ ($10^2$ acft). The maximum annual discharge of Maynard Creek, as estimated by Morrison and Maierle, Inc., 1978, is between 3 and $4 \times 10^6$ m$^3$ (2 and $3 \times 10^3$ acft)(Table 5, p. 51). Therefore, the maximum groundwater discharge from each surficial aquifer is no greater than about 3% of the maximum stream discharge of Maynard Creek. If the minimum annual discharge of Maynard Creek, as estimated by Morrison and Maierle, Inc., 1978, is $10^6$ m$^3$ ($10^3$ acft) (Table 5, p. 51), then the maximum yield from each surficial aquifer constitutes about 10% of the annual stream discharge. Therefore, the total
groundwater yields to surface flow from the Bridger and Deer Park aquifer is calculated to
be between 5% and 20% of the annual discharge of Maynard Creek.

The combined winter baseflow discharge from the Bridger and Deer Park aquifers to
the surface was measured to be approximately 7 lps (0.3 cfs), or about 12% to 25% of the
total baseflow of 28 to 56 lps (1 to 2 cfs) for Maynard Creek as measured by Williams
(1967). The baseflow (28 to 56 lps, 1 to 2 cfs) of Maynard Creek is sustained in part by
continuous yields of groundwater from the extensive undifferentiated till blanket that covers
over 60% of the catchment. If the Bridger and Deer Park aquifers discharge 7 lps (0.3
cfs), then the extensive till blanket contributes some fraction of the remaining baseflow of
21 to 49 lps (0.7 to 1.7 cfs). The total combined baseflow constitutes 10 to 20% of the
total annual yield of Maynard Creek. Therefore, the contribution of groundwater from the
catchment-sized, surficial Quaternary aquifer is less than 7 to 17% of the total annual yield
of Maynard Creek. If the total groundwater yields to the surface from the Bridger and Deer
Park aquifers is calculated to be between 5 and 20% of the annual discharge of Maynard
Creek, and the catchment-sized surficial aquifer contributes less than 7 to 17% of the total
annual surface discharge, then the catchment-sized aquifer and two isolated aquifers
account for less than 12 to 37% of the total annual yield of Maynard Creek as measured by
Williams (1967). The combined yields of all other springs in the catchment account for
much of the remaining surface water discharge.

Improved water collection at aquifer discharge areas is possible. Large groundwater
withdrawals during winter low flow periods could measurably affect the hydrologic regime
within the catchment. Community water consumption in cold climates varies considerably,
but minimum consumption is about 100 liters (26 gal) per person, per day (Armstrong and
others, 1980). If the winter day use at Bridger Bowl averages 1000 patrons, then the total
consumption within the catchment would be approximately $10^5$ liters (0.1 acft) per day, or
about $1.2 \times 10^7$ liters (12 acft) per winter season. The average water consumption rate
would be roughly $3.0 \times 10^6$ liters (3 acft) per month. Resort expansion and increased user
days at Bridger Bowl could result in water demands that are an order of magnitude greater
than this calculation. The estimated minimum winter discharges from Maynard Creek
during extended drought is between $1.0 \times 10^4$ and $1.5 \times 10^4$ m$^3$ (8 and 12 acft) per month
(Table 5, p. 51). The calculated minimum winter discharge from Maynard Creek during a
27 year period of record is between $1.4 \times 10^4$ and $2.0 \times 10^4$ m$^3$ (11 and 16 acft) per month
(Table 5, p. 51). Winter groundwater withdrawals from the entire catchment on the order
of approximately $3.0 \times 10^6$ liters (3 acft) per month could significantly reduce the total
discharge of Maynard Creek during minimum flow years.

If each isolated surficial aquifer discharges 3 lps (0.1 cfs) to the surface during winter
months, then a portion of this total is available for withdrawal and consumption. Each of
the two aquifers yield about $3 \times 10^5$ liters (0.2 acft) per day. Consequently, groundwater
withdrawals of $10^5$ liters (0.1 acft) per day from an isolated surficial aquifer could result in
large reductions in the discharge of the north or south fork of Maynard Creek during
baseflow periods, and also affect other spring discharges. This volume of withdrawal may
affect senior water rights on Maynard and Bridger Creeks and adversely influence local
stream biota. Induced recharge of surplus wastewater through sump holes or drain fields
would eventually produce return flows to Maynard Creek and may minimize adverse
affects of excessive groundwater withdrawals from the catchment.

The hydraulic character of the Quaternary deposits has significance to other
development activities that may occur in the catchment. Outwash and buried channel
deposits are highly conductive materials. They store and transmit much of the water used
in the catchment for human consumption. These materials are very vulnerable to surface
contamination due to the short residence time of the stored waters. Septic systems,
outhouses, maintenance facilities, and waste-water disposal outlets should not be placed on
or near these conductive deposits. These facilities are better situated on undifferentiated
tills that are well removed from groundwater recharge areas or down-gradient from any existing or anticipated groundwater development sites.
CONCLUSION

Surficial, unconsolidated Quaternary deposits in the Maynard Creek catchment do function as aquifers. The pattern of spring and seep distribution identifies groundwater discharge zones. Nearest Neighbor Indices of the spatial distribution of all springs and the most persistent springs indicate a strong clustering within surficial deposits. These spring distribution patterns are non-random and highly significant. Approximately 70% of the springs are concentrated in the lower half of the catchment. Also, the initiation of perennial stream flow on the north and south forks of Maynard Creek coincides with the central elevation where most springs exist. These patterns of groundwater discharge indicate that shallow groundwater flows into a lower topographic position which is occupied by thick, surficial Quaternary deposits.

Field evidence indicates that groundwater discharge features are physically connected to their storage sources. In the study area, 58 of 62 springs flow directly from surficial, unconsolidated deposits. At many locations, persistent high yield springs discharge from stable points that are located at the base of isolated Quaternary deposits. The most common morphologic associations between persistent springs and surficial deposits are: 1) springs discharging from glacial outwash deposits; 2) springs discharging from the base of moraines; 3) springs discharging from small sub-catchments; and 4) springs discharging from within active channels.

The stream discharge and flow duration characteristics of Maynard Creek both suggest that groundwater storage and discharge within the catchment is low. The stream hydrograph for Maynard Creek indicates that runoff is quick and most of the surface water
leaves the catchment in May and June. The baseflow is between 28 and 56 lps (1 and 2 cfs). The flow duration curve is characteristic of a steep stream system formed within less permeable geologic materials. The peak discharge is brief, and most of the total yield is sustained by direct surface runoff. The curve also indicates that groundwater storage and discharge exists, but is limited. Baseflow is less than 60 lps (2.1 cfs) for over seven months of the year, and as low as 20 lps (0.7 cfs) during the winter months. Groundwater discharge from the surficial aquifer system accounts for much of the total stream discharge during low flow and baseflow conditions.

The sensitivity of groundwater discharge and temperature to meteorologic occurrences and atmospheric temperatures also demonstrate that groundwater is stored in shallow, surficial unconsolidated deposits. Minor springs were reactivated by individual rainstorms. High yield springs showed rapid increases in discharge during and immediately after intense snowmelt runoff events. All spring yields steadily decreased after snowmelt runoff recharge occurred. Spring water temperatures can be depressed 0.8°C (1.4°F) by low temperature precipitation events. In general, the water temperatures of the most persistent springs decrease at a rate of about 1°C (1.8°F) per 100 m (328 ft) of elevation gained between spring locations. This rate of temperature change mimics the environmental lapse rate and is nearly equal to the theoretical dry adiabatic lapse rate.

The most productive and persistent spring identified in the catchment displays a water temperature regime that fluctuates with seasonal air temperature changes. The annual cycle of mean daily air temperature and spring water temperature both define a sinusoidal pattern. The peak in spring water temperature lags approximately 60 days behind the peak in mean daily air temperature.

Unconsolidated Quaternary aquifer discharge can be distinguished from bedrock aquifer discharge. First, springheads are physically connected to their source aquifers, which are bedrock units or surficial deposits. Second, surficial deposits discharge
groundwater enriched with calcium (Ca) and bicarbonate (HCO$_3$), and well waters derived from bedrock aquifers are sodium (Na) and bicarbonate (HCO$_3$) enriched. Third, groundwater discharge from surficial deposits can increase dramatically during snowmelt runoff events, but this was not observed from bedrock aquifers. Finally, temperature of surficial aquifer discharge is variable and affected by precipitation events, snowmelt runoff recharge, and air temperature, while bedrock aquifer discharge shows little temperature variability.

The water temperature regime of an individual spring defines a characteristic that distinguishes surficial and bedrock aquifer discharge. During spring and early summer months, bedrock aquifer discharge is consistently 1 to 3°C (1.8 to 5.4°F) higher than surficial aquifer discharge. The average temperature fluctuation of persistent surficial aquifer discharge is 1.9°C (3.4°F). The average temperature fluctuation of persistent bedrock aquifer discharge is 0.2°C (0.4°F). Those springs that are sustained by surficial aquifers tend to have lower winter temperatures, typically between 2.0°C (36°F) and 4.0°C (39°F), that increase to near the temperature of the bedrock aquifer waters by the end of the summer. Bedrock water temperatures were initially higher (about 5.0°C, 41°F) and were maintained throughout the period of observation.

Several Quaternary deposit types do not form surficial aquifers and contribute little to surficial aquifer functions. These deposits are talus, mass wasting, and modern alluvium.

Glacial deposits of three types are the primary components of surficial Quaternary aquifers. The deposits are rock glacier till, undifferentiated till, and outwash. The rock glacier till is a bouldery, clast-supported, matrix poor, and contains internal ridges and drain holes. The perimeter of the rock glacier is a 15 m (49 ft) high moraine. The interior of the deposit grades upward into a protalus rampart and talus slope. Two stable springs at the toe of the rock glacier moraine have a combined summer yield of 2 lps (0.07 cfs). The rock glacier forms a small and isolated aquifer.
Undifferentiated tills also function as components of surficial aquifers. These deposits were measured to be between 1 m (3.3 ft) and 20 m (66 ft) thick and cover over 60% of the catchment. The matrix of these tills is typically clayey, and rock content is high. The character of the till is highly variable, and laterally discontinuous zones of cobble and boulder supported tills with coarse matrix lie within the predominantly clayey deposits. Till stores useful quantities of water but releases it slowly over long periods of time. Undifferentiated tills maintain much of the Maynard Creek baseflow.

Glacial outwash forms distinct fans or chaotic deposits at three main areas in the catchment, and the deposits are at least 4 m (13.2 ft) thick. They consist primarily of poorly to well sorted sands, gravels, and cobbles. The glacial outwash deposits grade into or interbed with undifferentiated tills. The outwash deposits have sufficient volume and material characteristics to store and transmit useful volumes of groundwater, and do function as important components of surficial aquifers. Localized groundwater discharge zones occur in each main outwash deposit.

The surficial aquifer system within the Maynard Creek catchment is complex. The mosaic of all unconsolidated surficial materials, composed primarily of undifferentiated till, forms a large and poorly defined aquifer system. Also, small, isolated aquifers function within this larger, catchment-sized aquifer system. Two separate sub-catchments, Bridger and Deer Park, contain small aquifers that exemplify the characteristics of such small and isolated surficial, unconsolidated Quaternary aquifers.

The Bridger aquifer exists where undifferentiated till, coarse till, and buried channels form an isolated aquifer that sustains a residential water supply, contributes to annual stream flows, and maintains the baseflow of the north fork of Maynard Creek. The matrix-supported and clayey undifferentiated till sustains low but persistent groundwater discharge. Coarse, clast-supported till, thought to be outwash and dump moraine deposits, were located in the clayey undifferentiated till. Also, buried channels within the till were
detected with seismic refraction. A Giddings soil sampler was used to drill into a buried channel, and the saturated zone was intersected at approximately 180 cm (71 in) below the ground surface. The channel deposits were inspected during excavation for a spring development. The coarse till and network of channel deposits form preferred paths of subsurface flow that distribute groundwater to stable discharge points. Similar isolated aquifers exist elsewhere within the catchment.

The Deer Park aquifer is composed of undifferentiated till, outwash, and a buried channel network. The primary water source of the Deer Park day lodge, and the perennial flow of the main (south) fork of Maynard Creek, are sustained by groundwater discharge from this aquifer. Seismic refraction was used to identify the thicknesses and configuration of surficial unconsolidated deposits that overlie sandstone and shale bedrock.

Interpretations of data collected at the Deer Park aquifer indicate that undifferentiated tills sustain perennial baseflows to groundwater discharge zones in outwash. The buried channel network concentrates and distributes groundwater flow to stable discharge points. Ephemeral and intermittent groundwater discharge occurs through the outwash and buried channels.

Seismic refraction, material sampling, soil pits, excavations, and percolation tests were used to further characterize the Bridger and Deer Park aquifer. The thickness, area, and volume of the Deer Park aquifer were estimated. Also, values of porosity, storativity, and hydraulic conductivity of Quaternary deposits inspected during this investigation were approximated.

Bedrock units also function as aquifers and discharge into the Maynard Creek catchment. Fracture networks in bedrock create secondary porosity that facilitates water storage. As fracture density and secondary porosity decrease with increased depth, storage capacity diminishes and hydraulic conductivity is reduced. The less fractured zones force shallow groundwater flow to the surface through surficial materials. The steep dip of
bedrock aquifer units causes infiltrating waters to move vertically downward, thus being transported below and away from the catchment.

Only four of the 62 springs discharge from fractured bedrock. No bedrock aquifer springs were found to be perennial. Observations of groundwater discharges from bedrock outcrops indicate that these aquifer yields constitute only a minor portion of groundwater discharge into the catchment.

The groundwater development potential from surficial, unconsolidated Quaternary aquifers is constrained by available data. Although several important characteristics of the shallow groundwater regime within the Maynard Creek catchment have not been defined by this investigation, first approximations of the groundwater development potential from surficial aquifers can be estimated.

The surficial, unconsolidated Quaternary aquifers have limited development potential. Groundwater is concentrated in the Bridger and Deer Park aquifer areas where individual spring discharges range from less than 0.1 lps (0.002 cfs) to over 20 lps (0.7 cfs). The calculated amount of groundwater released from storage under the influence of gravity from each aquifer is about $10^5$ m$^3$ ($10^2$ acft). The total groundwater yields to surface flow from the Bridger and Deer Park aquifer is calculated to be between 5% and 20% of the annual discharge of Maynard Creek. The total discharges of the catchment-sized surficial aquifer and the two isolated surficial aquifers account for about 12 to 37% of the measured annual yield of Maynard Creek. The combined yields of all other springs in the catchment account for much of the remaining surface water discharge.

Improved water collection at aquifer discharge areas is possible. If the winter day use at Bridger Bowl averages 1000 patrons, then the average water consumption rate would be roughly $3.0 \times 10^6$ liters (3 acft) per month. Resort expansion and increased user days at Bridger Bowl could result in water demands that are an order of magnitude greater than this calculation. Winter groundwater withdrawals from the entire catchment on the order of
3.0 \times 10^6 \text{ liters (3 acft)} \text{ per month could significantly reduce the total discharge of Maynard Creek during minimum flow years.}

Each isolated surficial aquifer discharges about 3 lps (0.1 cfs) to the surface during winter months. This equals a yield of 3 \times 10^5 \text{ liters (0.2 acft)} \text{ per day from each aquifer. Consequently, groundwater withdrawal of 10^5 \text{ liters (0.1 acft)} \text{ per day from an isolated aquifer could result in large reductions in discharge of the north or south forks of Maynard Creek during baseflow periods, and reduce other adjacent spring discharges. This may affect senior water rights on Maynard and Bridger Creeks, and adversely influence local stream biota.}

The hydraulic character of the Quaternary deposits has significance to other development activities that may occur in the catchment. Outwash and buried channel deposits are highly conductive materials that store and transmit much of the water used in the catchment for human consumption. These materials are very vulnerable to surface contamination. Septic systems, outhouses, maintenance facilities, and waste-water disposal outlets should not be placed on or near these conductive deposits.
APPENDIX 1

Mississippian

Mission Canyon formation - The Mission Canyon formation consists of pale yellow-brown, massive, poorly bedded limestones. Outcrop exposures weather light gray and form cliffs and castellated ridges. The middle and upper parts of the formation contain chert and limestone nodules. The brown-weathered, irregularly shaped nodules contain fragments of limestone identical to the enclosing limestone beds. Solution and collapse breccias are common in the upper Mission Canyon formation. The Mission Canyon at Maynard Creek is a minimum of 155 meters thick.

Mississippian-Pennsylvanian

Big Snowy - Amsden strata - The Big Snowy - Amsden strata contain several distinct lithologic units. The basal unit consists of red, pink, purple, and lavender mottled, irregular-bedded, fine-grained dolomitic siltstones. Red and pink, massively bedded, interbedded, sandstone and silty sandstone units underlie a dark shaley limestone. The upper unit contains red and purple, hackly shales that quickly grade into pale-brown medium-bedded, fine-grained sandy dolomite. The contact with the overlying Quadrant formation is marked by the first thick quartzite bed. The Big Snowy - Amsden strata is 40 to 50 meters thick at Maynard Creek sites.

Pennsylvanian

Quadrant formation - The Quadrant formation is a prominent ridge forming unit that consists of white and light-gray, medium- to thick-bedded, cross-bedded, fine-grained, pure quartz sandstones. The formation thickness in the Maynard Creek catchment ranges from 20 to 30 meters.
Jurassic

Chert Breccia strata - The chert breccia unit contains chert and quartzite pebbles, and is locally conglomeritic. The breccia is contained in a yellow-brown, calcareous sandstone that overlies the Quadrant formation and underlies the Jurassic Ellis Group. At two localities in the Maynard Creek area the unit contains thin, variegated, calcareous shale zones. These shales were tested for phosphate, but yielded negative results (McMannis, 1955). A chert breccia layer found in the Maynard Creek catchment is 2 or 3 meters thick.

Ellis Group - The Ellis group contains three distinct formations (McMannis, 1955). The uppermost formation is the Swift, which weathers yellowish-brown and forms prominent ledges at Maynard Creek sites. The medium to thick, tabular, cross-bedded, sandstone and sandy limestone locally has a basal chert pebble conglomerate. The Rierdon formation consists of a dark gray, nonresistant, upper interbedded limestone and calcareous shale, and a basal massive oolitic limestone. The basal Sawtooth formation contains an upper red shale unit, and a lower, gray shale that is interbedded with silty limestone. The entire formation is exceptionally fossiliferous, and has a basal chert breccia that is locally conglomeritic. The thin, red to maroon shale at the top of the Sawtooth formation is thought to be a westward-extending tongue of the upper part of the Piper formation of central Montana; this tongue thins northward, and is not found north of the headwaters of Maynard Creek (McMannis, 1955). The Ellis Group is approximately 90 meters thick at Maynard Creek.

Morrison formation - In the Bridger Range the Morrison formation is poorly exposed, and few outcrops exist. At Maynard Creek, the predominantly variegated red and green, hackly shale has yellow-brown, silty sandstone units outcrop at mass movement sites on the southern catchment boundary. The formation also contains dark gray, fissile
shale. The Morrison formation is most notable for its slope instability. At the headwaters of Maynard Creek, the formation is 96 meters thick (McMannis, 1955).

**Lower Cretaceous**

**Kootenai formation** - The Kootenai formation is poorly exposed within the catchment, but elsewhere has been divided into three parts: 1) a thick, basal, white, gray, and pink stained, massive, cross-bedded, coarse-grained, locally conglomeritic sandstone is a mixture of black chert and quartz grains; 2) the middle portion is poorly exposed, and outcrops only at the southern margins of the Maynard Creek catchment. It consists of variegated red, purple, and maroon shales and mudstones, interbedded with red weathering argillaceous sandstone; 3) The upper portion is an iron-stained, medium- to thick-bedded, fine-grained, pure quartzose sandstone (McMannis, 1955). Characteristic fossils include plant fragments and locally abundant gastropods. The formation was not sub-divided during this investigation. The Kootenai formation is thought to be overthickened by oblique lateral faulting in the southern catchment, and ranges from 140 meters to 180 meters in thickness.

**Upper Cretaceous**

**Colorado formation** - The Colorado formation is poorly exposed in the Maynard Creek catchment, but has one outcrop south of the catchment boundary. At this location, the nonresistant, dark gray, iron-stained, marine shale is interbedded with gray-green, thin-bedded sandstone. The upper member (Cody shale), (Skipp and McMannis, 1971) contains numerous fossils that belong to the Class Bivalvia. Elsewhere in the Bridger Range, the Colorado formation has been sub-divided into the Cody, Mowry-Thermopolis, and Frontier members (Skipp and McMannis, 1971), and contains fossils from the Class Cephalopoda (Lupton, 1916). No attempt has been made during this investigation to
subdivide the formation into members. The calculated thickness of the Colorado formation is 350 to 400 meters.

**Telegraph Creek formation** - The Telegraph Creek is poorly exposed in the Maynard Creek catchment, but the formation consists of orange-gray to dark green-gray, thin-bedded, locally cross-bedded, biotite-rich, shaley sandstones and dark gray marine shales (Skipp and McGrew, 1977). The unit contains numerous lime nodules and fossils of the Class Cephalopoda (Thom and Dobbin, 1924).

**Eagle formation** - The Eagle formation is a prominent ridge forming unit in the Maynard Creek catchment. The formation is thought to have gradational contacts and can be located only to within 100-200 feet (McMannis, 1955), and represents a transition from marine to non-marine depositional environments (Weed, 1899). The light gray, thin-bedded, locally cross-bedded, fine- to medium-grained, biotite-rich sandstone contains intercalated carbonaceous shales and very thin coal seams (McMannis, 1955). The formation is locally calcareous, lime nodule bearing, contains plant fossils and pelecypods (Weed, 1893). The thickness of the Eagle formation is approximately 100 to 140 meters.

**Livingston group** - The resistant members of the Livingston group are well exposed throughout the lower Maynard Creek catchment. The members of the group existing within the catchment include the Sedan formation and the Billman Creek formation. The individual members of the Sedan formation are well exposed at widely spaced locations, while the Billman Creek formation is poorly exposed in the catchment.

**Sedan formation** - The Sedan formation consists primarily of nonmarine epiclastic volcanic sandstone, mudstone, and conglomerate interbedded with volumetrically less important mudflow conglomerate, welded tuff, devitrified, silicified, vitric tuff, bentonite, and lignitic coal (Skipp and McGrew, 1977). The Sedan formation has been formally
divided into six members. The members are: 1) the lower sandstone member; 2) the welded tuff member; 3) the middle sandstone member; 4) the Bearpaw Shale Member; 5) the mudstone member; and 6) the Lennep Sandstone Member (Skipp and McGrew, 1977).

The Bearpaw Shale is not found in the catchment (Skipp and McMannis, 1971).

**Lower Sandstone Member** - Epiclastic volcanic sandstone, siltstone, mudstone, porcelanite, and silicified devitrified crystal lithic tuff interbedded with minor granule and pebble conglomerate and lignitic coal make up the member (Skipp and McGrew, 1977). The sandstone is olive-gray, greenish-gray, and yellowish-gray, weathers brown, is fine-grained to conglomeritic, medium-bedded, locally cross-bedded, calcareous, ironstone nodule bearing, with abundant plant fossils (Skipp and McGrew, 1977). The lower sandstone member ranges in thickness from 180 to 220 meters.

**Welded Tuff Member** - The welded tuff member is a prominent ridge former in the catchment. The welded tuff member consists of pale yellowish-green, greenish-gray, grayish-red, and reddish-brown sheets and welded tuff, separated by olive-gray volcanic and quartzose sandstone, dark colored conglomerate and mudstone, and dark greenish-gray to gray porcelanite and altered vitric tuff. The unit is fine-grained and contains locally abundant phenocrysts of golden-weathering biotite, crystals of labradorite, andesine, augite, hypersthene, volcanic shards and pumice fragments, and small clasts of altered volcanic rock. Conglomerate composed of welded tuff pebbles and cobbles mark the base and top of the unit. Wood fragments are present throughout (Skipp and McGrew, 1977). The welded tuff member is approximately 180 to 200 meters thick.

**Middle Sandstone Member** - The middle sandstone member comprises a ridge-forming series of epiclastic volcanic sandstones interbedded with epiclastic volcanic conglomerate, mudflow conglomerate, and minor volcanic siltstone and mudstone. The
sandstones are olive-green, olive-gray, dark greenish-gray, fine-grained to conglomeritic, calcareous, cross-bedded, and composed of feldspar, volcanic rock fragments, hornblende, augite, quartz, iron-oxide minerals and clays. Wood fragments are sparse (Skipp and McGrew, 1977). The middle sandstone member is 250 to 280 meters thick.

**Mudstone Member** - The mudstone member is a poorly exposed, valley forming interval that contains poorly-bedded varicolored gray, green, brown, red, and yellow volcanic mudstone, much of which is siliceous, bentonitic, and calcareous in places. The mudstone is inter-bedded with green and gray, fine-grained to conglomeritic, tuffaceous, partly calcareous, epiclastic volcanic sandstone (Skipp and McGrew, 1977). The unit is 210 to 240 meters thick.

**Lennep Sandstone Member** - The Lennep sandstone member is poorly exposed in the Maynard Creek catchment. It consists of a lower series of olive-gray, greenish-gray, and pale orange, thin medium- to coarse-grained sandstone lenses inter-bedded with siliceous mudstone and devitrified vitric tuff. The upper part is marked by a yellow-brown, thick coarse-grained calcareous sandstone that is overlain by gray and brown volcanic mudstone and friable, cross-bedded, magnetite-rich sandstone and conglomerate lenses. Epiclastic volcanic pebble and conglomerate lenses are common (Skipp and McGrew, 1977). Characteristic fossils are not known for the Lennep sandstone (Stone and Calvert, 1910). The unit is approximately 300 meters thick.

**Billman Creek formation** - The Billman Creek formation is generally covered in the catchment. The few outcrops consist of gray-green, gray-brown, red-brown, and purple-brown, mudstones, siltstones, and volcano-clastic sandstones. The gray-green to gray-red, thin fine- to medium-grained, well-sorted, chert, magnetite-rich, quartz sandstone
is inter-bedded with dark gray-green, thin-bedded, fissile shale. The unit has an undetermined thickness.

**Quaternary**

The Quaternary stratigraphy of the Maynard Creek catchment is complex, and its description is inherently interpretive. Very general geomorphological mapping of the Maynard Creek catchment describes all surficial deposits as glacial undifferentiated (Locke and others, 1985). Detailed mapping has been completed for catchments immediately north of Maynard Creek (Schrunk, 1976; Locke and others, 1985). The following description of Quaternary deposits infers that similar age deposits exist in the Maynard Creek catchment.

**Pleistocene**

The catchment morphology has been extensively modified by pre-Wisconsin erosion (early-Pleistocene), through alpine neoglaciacion (mid-Holocene), and modern periglacial processes (late-Holocene). Distinct glacial depositional episodes (Bull Lake through post-Pinedale) have resulted in a highly variable accumulation of blanket till and morainal sequences. It is likely that till diamictons have incorporated a significant portion of mass movement material, resulting from bedrock failures onto the existing diamicton, and reworking within by unstable flowage till. Modern mass movement events are evident in the catchment, and result in continual accumulation of surficial deposits. The diamictons and till are locally and unconformably covered by Holocene colluvial deposits; typically coalescing talus cones. Surficial materials were estimated to be 0 to 30 meters thick (Montagne, 1978).
APPENDIX 1 - Continued

Holocene

A mosaic of Holocene surficial deposits have resulted from a final glacial retreat (mid-Holocene) (Shaw, 1988), and a continuation of colluviation, mass movement, and periglacial weathering. Included within this mosaic are regolith, talus, various mass wasting debris, pro-talus ramparts, till, and a relict rock glacier. In addition, modern alluvial processes have performed extensive modification of many surficial materials, as evidenced by active gully and channel networks, channel levees, glacio-sediment reworking, and outwash accumulations. Finally, the periglacial and gravitational processes of solifluction, gelifluction, and frost wedging, in conjunction with immature to mature soil development, have made a notable contribution to the current slope morphology in the Maynard Creek catchment. Thickness of these deposits has been inferred as 0 to 20 meters.
References


References - Continued


References - Continued


References - Continued


References - Continued


References - Continued


Moore, B.K., 1984, Controls on ground-water availability and quality, the Bridger Canyon area, Bozeman, Montana [M.S. thesis]: Bozeman, Montana State University, 187 p.


References - Continued


SURFACE HYDROLOGY
MAYNARD CREEK CATCHMENT
BRIDGER RANGE, MONTANA
JUNE 1991

Spring Discharge Class
- Low Discharge Volume Springs, 4 - 20 Ipm (1 - 5 gpm)
- Medium Discharge Volume Springs, >20 - <80 Ipm (>5 - <20 gpm)
- High Discharge Volume Springs, >80 Ipm (>20 gpm)
- Developed Springs, oil >80 Ipm May - October (>20 gpm)

Spring number refers to data in text.

Stream Network
- Zero Order Streams (Ephemeral or Perennial, Channelized Spring or Seep Flow)
- First Order Streams (Ephemeral)
- Second Order Streams (Perennial)
- Third Order Streams (Perennial)

Surface Water
- Seeps - Localized points of diffuse ground water or soil water discharge
- Standing Waters - Broad areas of standing, unconfined surface waters
- Natural Ponds - Very small sag ponds
- Engineered Ponds - Small surface water containment structures

Scale 1:8000
Contour Interval 40 Feet
Field mapping completed by John F. Whittingham
Based on field data collected during 1990 and 1991
SURFICIAL GEOLOGY
MAYNARD CREEK CATCHMENT
BRIDGER RANGE, MONTANA

Type of Deposit

- Bedrock (Undifferentiated) - Mississippian through Cretaceous sedimentary rubble mat forms cone-like deposits at the base of propping dipping to vertical units contain fractures, faults, and lineaments. Strata of limestone, sandstone, shale, and Tertiary igneous intrusives. West matrix supported debris. Moraines and mass wasting occurrences common.

- Glacial (Undifferentiated) - Thick blankets and thin veneers of sub-, intraglacial deposits found downslope of moraine crests and/or supraglacial deposits. Typically coarse cobble-boulder, sandy-clay, and matrix-supported debris. Moraines and mass wasting occurrences common.

- Glacial (Rock Glacier) - Predominantly angular bedrock rubble blocks found downslope of moraine crests and/or supraglacial deposits. Typically coarse cobble-boulder, sandy-clay, and matrix-supported debris. Moraines and mass wasting occurrences common.

- Glacial (Outwash) - Predominantly coarse (0.1-1.0 m), moderately sorted, angular deposits found downslope of moraine crests and/or supraglacial deposits. Typically coarse cobble-boulder, sandy-clay, and matrix-supported debris. Moraines and mass wasting occurrences common.

- Alluvium (Stream) - Deposits of well to moderately sorted, often stratified, and/or channel materials consisting of remnant cobbles and boulders. Mass wasting occurrences common.

- Alluvium (Lake) - Deposits of well sorted, stratified, fine sand, silt, and clay. Mass wasting occurrences common. Type of movement defines mass wasting class (Varnes, 1978). Often gradual or combined with other mass wasting types.

- Debris fall (d1) - Earth fall (e1) - Deposition of unstratified coarse debris. Type of movement defines mass wasting class (Varnes, 1978). Often gradual or combined with other mass wasting types.

- Debris fall (d2) - Earth fall (e2) - Deposition of unstratified coarse debris. Type of movement defines mass wasting class (Varnes, 1978). Often gradual or combined with other mass wasting types.

- Lateral spread (r4) - Earth slump (e3) - Deposition of unstratified coarse debris. Type of movement defines mass wasting class (Varnes, 1978). Often gradual or combined with other mass wasting types.

- Rock flow (r7) - Earth slope (e5) - Deposition of unstratified coarse debris. Type of movement defines mass wasting class (Varnes, 1978). Often gradual or combined with other mass wasting types.

- Rock topple (r2) - Debris topple (d) - Deposition of unstratified coarse debris. Type of movement defines mass wasting class (Varnes, 1978). Often gradual or combined with other mass wasting types.

- Free fall and tumbling of freeze-thaw fragments. Mass wasting occurrences common.

- Mass wasting classification (Varnes, 1978). Often gradual or combined with other mass wasting types.

- Mass wasting classification (Varnes, 1978). Often gradual or combined with other mass wasting types.

- Mass wasting classification (Varnes, 1978). Often gradual or combined with other mass wasting types.

- Mass wasting classification (Varnes, 1978). Often gradual or combined with other mass wasting types.

- Mass wasting classification (Varnes, 1978). Often gradual or combined with other mass wasting types.
MAYNARD CREEK CATCHMENT

30 Trend and plunge of lineation
Vertical bedding
Approximate contact (+/- 15 meters)

BRIDGER RANGE, MONTANA

Interpretations, field mopping, and cartography completed 1993 by John F. Whittingham

Extent of outcrop exposure. Strike and dip of overturned bedding

Inferred contact • Fracture trace projected beneath overburden

Very approximate contact (+/- 25 meters)

GENERALIZED STRATIGRAPHIC SECTION

Sedan formation, Lower Sandstone Member - Olive-green to yellow-brown, brown, fine- to medium-grained sandstone, the group has been divided to the Cody, Morrey-feralopolis, and frontier formations.*

Sedan formation, Welded Tuff Member - Yellow-green to red-brown, massive, poorly bedded, yellow-brown, silty sandstone, the formation also contains sandstone and sandy limestone; 2) Rierdon1 oolitic limestone, 3) big-snowy Pueblo, a red-loved, mottled dolomitic siltstone.

Sedan formation, Middle Sandstone Member - Olive-green to dark gray, brown, fine- to medium-grained sandstone lenses inter-bedded with shale.*

Colotodo Group - Dark gray, iron-stained marine shale inter-bedded with conglomeritic, epiclostic volcanic sandstones, 2) o red, variegated massive conglomeritic sandstone, 3) big-snowy Pueblo, a red-loved, mottled dolomitic siltstone.

Quadrant, a white quartz sandstone, 2) Amsden1 a red-purple shale; 3) big-snowy Pueblo, a red-loved, mottled dolomitic siltstone.

Ellis Group - The group contains three formations 1) uppermost Mission Canyon Formation - A yellow-brown, massive, poorly bedded sandstone and siltstone, the formation also contains numerous dark gray, fissile shale beds, and cool seams.

3) bosoi saw tooth, a red shale and silty limestone.

Switt contains sandstone and sandy limestone; 2) Rierdon1 oolitic limestone, 3) big-snowy Pueblo, a red-loved, mottled dolomitic siltstone.

Eagle Formation - Light gray, thin-bedded, locally cross-bedded, biotite-rich, shaley sandstone and dark gray marine shale, 2) red, variegated massive conglomeritic sandstone, 3) big-snowy Pueblo, a red-loved, mottled dolomitic siltstone.

Telegraph Creek Formation - Dorl gray-green, thin-bedded, locally fine- to medium-grained, biotite-rich, salt- and pepper sandstone, the group has been divided to the Cody, Morrey-feralopolis, and frontier formations.*

Porcelain formation, lower Sandstone Member - Olive-green to yellow-brown, brown, fine- to medium-grained sandstone, the group has been divided to the Cody, Morrey-feralopolis, and frontier formations.*

weathering epiclostic volcanic sandstone, siltstone, mudstone, welded tuff conglomerate, mudflow conglomerate, and mudstone.

Epiclostic volcanic pebble conglomerate, mudflow conglomerate, and mudstone.

a lamprophyre, the dike is a result of composite intrusions.

Dike - The dike is a porphyritic, pendiomorphic, debris, colluvio deposits, fluvial deposits, and diamictons.

Pleistocene glacio deposits, periglacial deposits, moraine westing

Undifferentiated - A complex mosaic of Holocene and Pleistocene deposits, weathering products, silicified devitrified crystal lithic tuff.

Gas containing numerous dark gray, fissile shale beds, and cool seams.

Sedan formation, lower Sandstone Member - Olive-green to yellow-brown, brown, fine- to medium-grained sandstone, the formation also contains sandstone and sandy limestone; 2) Rierdon1 oolitic limestone, 3) big-snowy Pueblo, a red-loved, mottled dolomitic siltstone.

Sedan formation, Welded Tuff Member - Yellow-green to red-brown, massive, poorly bedded, yellow-brown, silty sandstone, the formation also contains sandstone and sandy limestone; 2) Rierdon1 oolitic limestone, 3) big-snowy Pueblo, a red-loved, mottled dolomitic siltstone.

Sedan formation, Middle Sandstone Member - Olive-green to dark gray, brown, fine- to medium-grained sandstone lenses inter-bedded with shale.*

Colotodo Group - Dark gray, iron-stained marine shale inter-bedded with conglomeritic, epiclostic volcanic sandstones, 2) o red, variegated massive conglomeritic sandstone, 3) big-snowy Pueblo, a red-loved, mottled dolomitic siltstone.

Quadrant, a white quartz sandstone, 2) Amsden1 a red-purple shale; 3) big-snowy Pueblo, a red-loved, mottled dolomitic siltstone.

Ellis Group - The group contains three formations 1) uppermost Mission Canyon Formation - A yellow-brown, massive, poorly bedded sandstone and siltstone, the formation also contains numerous dark gray, fissile shale beds, and cool seams.

3) bosoi saw tooth, a red shale and silty limestone.

Switt contains sandstone and sandy limestone; 2) Rierdon1 oolitic limestone, 3) big-snowy Pueblo, a red-loved, mottled dolomitic siltstone.

Eagle Formation - Light gray, thin-bedded, locally cross-bedded, biotite-rich, shaley sandstone and dark gray marine shale, 2) red, variegated massive conglomeritic sandstone, 3) big-snowy Pueblo, a red-loved, mottled dolomitic siltstone.

Telegraph Creek Formation - Dorl gray-green, thin-bedded, locally fine- to medium-grained, biotite-rich, salt- and pepper sandstone, the group has been divided to the Cody, Morrey-feralopolis, and frontier formations.*

Porcelain formation, lower Sandstone Member - Olive-green to yellow-brown, brown, fine- to medium-grained sandstone, the formation also contains sandstone and sandy limestone; 2) Rierdon1 oolitic limestone, 3) big-snowy Pueblo, a red-loved, mottled dolomitic siltstone.

Sedan formation, Welded Tuff Member - Yellow-green to red-brown, massive, poorly bedded, yellow-brown, silty sandstone, the formation also contains sandstone and sandy limestone; 2) Rierdon1 oolitic limestone, 3) big-snowy Pueblo, a red-loved, mottled dolomitic siltstone.

Sedan formation, Middle Sandstone Member - Olive-green to dark gray, brown, fine- to medium-grained sandstone lenses inter-bedded with shale.*

Colotodo Group - Dark gray, iron-stained marine shale inter-bedded with conglomeritic, epiclostic volcanic sandstones, 2) o red, variegated massive conglomeritic sandstone, 3) big-snowy Pueblo, a red-loved, mottled dolomitic siltstone.

Quadrant, a white quartz sandstone, 2) Amsden1 a red-purple shale; 3) big-snowy Pueblo, a red-loved, mottled dolomitic siltstone.

Ellis Group - The group contains three formations 1) uppermost Mission Canyon Formation - A yellow-brown, massive, poorly bedded sandstone and siltstone, the formation also contains numerous dark gray, fissile shale beds, and cool seams.