APPENDIX D

Meeting Data Needs to Perform a Water Impact Assessment for Oil Shale Development in the Uinta and Piceance Basins

A Subpart of Project
Quantifying Water Availability Impacts and Protecting Water Quality While Developing Utah Oil Shale and Sands

Final Project Report
Reporting period: June 21, 2006 to October 21, 2009

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Project Title: Meeting Data Needs to Perform a Water Impact Assessment for Oil Shale Development in the Uinta and Piceance Basins

Principal Investigator: Steve Burian, Ph.D., P.E., Assistant Professor, University of Utah

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Researchers Supported: Eric Jones (part-time hourly undergraduate researcher; fall 2007 – fall 2008), Woo Suk Han (2 months, graduate research assistant, summer 2008), Greg Nash (1 month, research scientist with EGI, spring 2008), Beth Dudley-Murphy (1 month, research scientist with EGI, summer 2008)

Project Tasks as Originally Proposed:
1. Collect Literature and Create GIS Database of Water Resources Data
2. Quantify Water Requirements for Future Oil Shale Development Projections
3. Develop a Methodology to Assess Water Availability

Summary of Project Outcomes:
1. The literature review produced more than 50 documents that are being incorporated into the Utah Heavy Oil Program (UHOP) Repository (http://ds.heavyoil.utah.edu/dspace/index.jsp). The geospatial datasets collected and created are being incorporated into the UHOP map server (http://map.heavyoil.utah.edu/website/uhop_ims/viewer.htm).

2. To update water requirements estimates, we needed to project urban growth, estimate available oil shale resources, and quantify water requirements for the urban growth, oil shale industry, and energy generation sectors. The Eastern Utah urban growth projection was based on a retrospective analysis of growth in Fort McMurray, Canada, in response to their oil sands development growth. The retrospective analysis provided a model to follow that was fine-tuned in discussions with Vernal planning department officials to arrive at a reasonable estimate of future urban growth and to generalize key characteristics of the urban demographic and growth pattern likely to influence water demand. The in-place oil shale resource estimates were based on a geostatistical analysis. Water demand estimates were made using a range of possible oil shale production rates, technologies, and urban and energy water demands.

3. A methodology to determine water availability was conceived. The conceptual approach identified the need to develop a water management model for the White River (a tributary to the Green River in the Colorado River Basin), to acquire and incorporate hydrologic information, and to accurately account for the current water users in the region.
**Project Goal**

The goal of this project was to mitigate water resources impacts from oil shale development in the U.S. by compiling geospatial data and water use estimates to assess water availability impacts.

**Objectives**

To meet the project goal, we (1) completed a brief literature search to acquire publications and fact sheets on oil shale and water resources, (2) collected water resources geospatial datasets for the Uinta and Piceance Basins in Utah and Colorado to support the development of the water management model, (3) studied urban growth in the Uinta Basin to improve population projections, (4) determined revised oil-yield estimates for the Uinta-Piceance Basins, (5) developed updated estimates of water demand for oil shale development in the Uinta and Piceance Basins and compared to previous estimates, (6) quantified changes to past water demand estimates for a range of development scenarios including advances in oil shale extraction technologies, alternative energy generation, and sustainable urban growth, and (7) defined a conceptual approach to assess water available for oil shale development. Summaries of the effort and outcomes of the research are described below.

**Background**

Currently, oil supplies more than 40% of our total energy demands and more than 99% of the fuel we use in our cars and trucks [1]. The U.S. is the largest consumer of oil in the world, consuming approximately 20 million barrels of oil a day [2]. This daily usage is increasing by 2% every year and, if the trend continues, by the year 2030 the U.S. will consume over 30 million barrels of oil a day (Figure 1). Oil production in the U.S. is insufficient to meet this need; therefore, the U.S. imports 10.4 million barrels of oil per day [1]. The demand for oil in the U.S. is increasing in concert with the general demand for energy. The national consumption of electricity per capita (residential) has increased from 3,167 kWh/person/year in 1980 to 4,223 kWh/person/year in 2001, representing an annual average increase of 48 kWh/person/year. If this trend continues, by 2030 the electricity consumption will be 5,327 kWh/person/year [2]. To successfully meet increasing energy demand and to reduce dependence on foreign oil there is a national need to develop, in an economically and environmentally sustainable manner, domestic oil resources.
In the U.S., unconventional hydrocarbon resources, including heavy oil, oil sands, and oil shale, represent significant potential domestic oil sources. The U.S. Heavy Oil Database [3] estimates heavy oil in the U.S., not including Alaska, to be 84.2 billion barrels, mostly located in California. The U.S. oil sands resource is estimated at 54 billion barrels original oil in place (OOIP), in the form of bitumen [4]. The largest oil sands deposits in the U.S. are in Utah with proven reserves of 8-12 billion OOIP in the form of bitumen [5]. The Green River Formation in Colorado, Utah, and Wyoming is, volumetrically, the largest oil shale resource in the U.S. (Figure 2) with resource estimates of 1.5-1.8 trillion barrels OOIP [5]. At an estimated production rate of 5 million barrels of oil per day this source could meet more than one-quarter of the U.S. demand for more than 500 years. Figure 2 indicates the locations of deposits with different qualities as estimated by the National Energy Technology Laboratory (NETL). The dark gray areas are underlain by an estimated 10-foot thick layer of oil shale, which could potentially produce 25 to 50 gallons or more of oil per ton. The lighter brown areas are either unapprised or low-grade.

**Figure 2.** Location of oil shale [38].
Oil shale in the U.S., however, has not been considered a feasible source of energy to date because of many factors, including high development costs, environmental impacts, and water availability. Newer, more cost-effective technologies are still being developed; however, current cost estimates range from $10 to $95 per barrel [6]. These prices are becoming more competitive with recent and possible future crude oil prices (Figure 3); thus, there is renewed interest from industry as well as local, state, and federal governments to commercially develop this resource. Although the contents of this report have applicability to heavy oil, oil sands, and oil shale, the focus is on oil shale.

![Figure 3. Crude oil price projections [2].](image)

Oil shale is comprised of fine-grained sedimentary rock bound with kerogen [5]. When the rock-kerogen mixture is heated, petroleum-like liquids are released [7]. There are essentially two methods to develop oil shale – (1) mining and surface retorting and (2) in situ retorting. Both require water to execute the process. Mining can be subdivided into surface mining and underground mining, with underground mining having limitations of recovery rate and greater safety risk. Surface mining is more effective and can produce much higher resource extraction, although overburden deposited on the surface is an environmental concern requiring reclamation attention. Regardless of mining technique, the oil shale is crushed at the surface and retorted at 900~1000 ºF in a surface retorting plant to produce shale oil from kerogen in the rock. In order for either method to be profitable, the operating and maintenance costs for the plant should be $17 to $23 (2005 dollars) per barrel of oil produced [8]. However, estimates of cost for mining and surface retorting indicate that the price of low-sulfur, light crude oil would have to be at least $70 to $95 per barrel for an oil shale operation to be profitable [7]. An estimate of water required for mining and surface retorting processes is approximately 1 to 3 gallons water/gallon of oil produced [7].

In situ retorting during the 1970s and 1980s involved dewatering, fracturing, heating, recovering, and transporting processes [5]. A newer approach, the In Situ Conversion Process (ICP), was introduced in the early 1980s by Shell [7]. Their process involves drilling a series of boreholes into an oil shale deposit and installing underground heaters. Heaters are placed in the boreholes and the deposit is heated to 650-700ºF for 2 to 3 years, after which the oil is extracted using conventional methods. The ICP approach has resolved many of the disadvantages of mining and
surface retorting. First, it reduces the potential for air and water pollution, although the issues of groundwater pollution after the freeze wall thaws out are unknown. Second, it eliminates surface destruction, although in situ processing does have a footprint [9]. Third, it has the potential to reduce costs. Estimates of ICP water requirements could not be found. However, since the process requires substantial amounts of energy to execute the heating process, water requirements will depend on the energy generation technique.

Oil shale development in the U.S. will impact water resources, especially in the semi-arid western states. To begin to re-assess the potential water resources impacts, it is necessary to review past studies, collect geospatial and environmental datasets for analysis, update estimates of population and of oil shale reserves, estimate water requirements for future oil shale industry growth, and identify water availability constraints. The beginning steps towards these needs are addressed by the research described herein. Further research is needed to provide greater breadth and depth to the analyses presented here, to develop and implement the water availability assessment framework, and to investigate possible surface water and groundwater impacts.

Task 1. Literature Search and GIS Dataset Compilation

Literature Search Summary
During the first oil shale boom in the 1970s and 1980s, a considerable amount of research was performed to address the water resources issues [8]. With the renewed interest of the past decade in unconventional oil resources, including oil shale, the research has been repeated and extended to further address the potential water resources issues associated with oil shale development. The first phase of the present project involved compiling key literature references and uploading them to the Utah Heavy Oil Program (UHOP) repository [10]. Of the approximately 50 documents (including reports, journal papers, fact sheets, and conference papers), two stand out as the key resources: reports by the Office of Technology and Assessment (OTA) [8] and the RAND Corporation [7]. The first provides an extremely detailed description of their approach to estimate the water requirements and identifies alternative approaches to supply the needed water in the western U.S. regions. The RAND report essentially updates the OTA assessment but uses an estimate of water required for oil shale extraction and processing of 1 to 3 barrels of water per barrel of oil produced compared (compared to 2-5 barrels used in the OTA estimate). The reduced amount of water was justified based on improved technologies. Key findings from the literature review included:

- From the time of the OTA report [8], the potential alternatives to supply water for oil shale development remain essentially the same, but additional sources including deep groundwater, wastewater recycle and water reuse, and new opportunities for storage and water development projects increases options and flexibility [8].
- Recent advances in produced water treatment technologies have reduced potential environmental impacts [11].
- Past failures of oil shale industry were due to reasons other than the resources [12].
- Examples of recent oil shale and oil sands production in other countries provide important information of use in assessment of water resources impacts of oil shale development in the U.S. Specific information related to water provided in the recent
literature address urban growth, demographics, and environmental impacts [e.g., 13,14,15].

- A start-up period associated with early growth of an oil shale industry must be expected. Reductions in water requirements and water resources impacts as the industry matures must also be expected based on the experiences over the last 35 years with the Alberta oil sands. Estimates of water requirements must consider the likely reductions as the industry matures.

- Advances in the 1980s and 1990s have reduced water requirements for traditional oil shale extraction and processing techniques from 2-5 barrels or water per barrel of oil to 1-3 barrels of water per barrel of oil [7].

- The Shell Oil Co. ICP has the potential to reduce (or in some cases eliminate) environmental impacts and significantly reduce the amount of water use [12], but there are new uncertainties associated with heretofore unforeseen environmental impacts (e.g., impacts to groundwater quality).

- Development of other energy industries in Utah, Colorado, and Wyoming has established a strong infrastructure backbone and new environmental technologies for the oil shale industry.

- Inclusive approach of Alberta for oil sands development could serve as a model to minimize social and cultural impacts [12].

- A geospatial approach to water management is needed to overcome the water limitations in the western U.S.

- A search of the Utah Division of Water Rights online resources indicates private owners of oil shale lands in Utah have already secured senior water rights to supply projects. The state Division of Water Resources also holds water rights for possible growth in the region. Oil shale leases on federal lands, however, will not come with water rights, and more than 80% of the Green River Formation lies on federal land.

**GIS Datasets Summary**

In addition to a brief literature review to give a background and provide a base level of understanding of the current state of the practice, the project team also collected GIS datasets related to oil shale and water resources in the Uinta and Piceance Basins from the Colorado Division of Water Resources, the Utah Division of Water Rights, the Utah Geological Survey, and the U.S. Geological Survey. In sum, more than 50 geospatial datasets were collected and compiled into a listing describing the datasets. The datasets describe the oil and gas resources in the Uinta and Piceance Basins and a range of water-related datasets – natural and human. The GIS data has been supplied to UHOP for upload to their map server [16]. The datasets describe the spatial distribution of the hydrography, energy resources, transportation networks, and urban population as well as the terrain and land use features of the areas. Consideration based on the data collection and literature review compilations resulted in the identification of the need to acquire environmental data and hydrologic data in time series format to help characterize the baseline environmental quality of the area.
**Task 2. Revised Estimates of Water Requirements for Oil Shale Development**

For this task, previous estimates of water requirements for oil shale development in the Uinta and Piceance Basins were reviewed and a new estimate was made based on recently available information and new approaches. Two new sub-tasks were needed: urban growth projection and estimate of oil shale resources.

**Urban Growth Estimate**

Urban growth projections can be made in a number of ways. The projection made in 1980 by OTA [8] has been used to some extent by all known estimates of water requirements for oil shale development in the Uinta and Piceance Basins. The OTA municipal population growth projection was assumed to be 5.5 times the number of employees. This was identified as an “uncertain estimate” by OTA. For our estimate, we used the 20+ year growth of the town of Fort McMurray, Alberta, Canada, to represent a reasonable model of the growth of the small town of Vernal in Eastern Utah. This growth model provided us with population projections to grow the oil shale industry from no commercial development to 2-3 million bbl/day of oil produced.

The first step of the analysis was the acquisition of aerial photos of the two cities for two periods in time. The aerial photos of Vernal, Utah were obtained for 1997 and 2006 (Figures 4 and 5), a approximately 10-year period of slow population growth in the city. Observing the photos, one notes the increase of urban areas to the east and south of the central town site in the 2006 image compared with the 1997 image. It is important to note the importance of the existing transportation corridors on the pattern of growth observed. A spatial pattern of growth (not made for this study) would likely concentrate along the same transportation corridors followed by the 10-year growth ending in 2006.
Discussions with urban planners from Vernal indicated that population growth has actually been higher than the two images suggest, especially over the past 3-4 years as the energy development
industry has grown. There is no significant outward growth of the city yet due to building policies and prices. Most of the people moving in to town are renting every available space and even moving into work sheds and fixing them up to simulate small cabins. There is some growth that is visible from a close study of the images, but not enough to compensate for the change in total numbers.

This housing shortage is a major problem facing Vernal. The Vernal planners suggested this trend is not due to lack of homes but a lack of affordability. In fact, homebuilding is at an all time high in the area. Single-family home building permits numbered 41 in Vernal City in 2005. This number ballooned to 61 in 2006 and 68 in the first nine months of 2007. At a meeting in Vernal in 2008 [17], a development company addressed a large gathering to discuss housing shortages and housing prices in Vernal. The key points from the meeting were the relative “lack of workforce housing for moderate-income homeowners in the community”. Homes have increased in value 30 percent over the past couple of years. With the average home valued at $200,000, many first-time buyers are priced out of the market. While new construction continues, mid-range construction for lower income qualifiers has not. Some families are living in recreational vehicles and others, in their cars. A 72-year-old woman reported at the meeting that rising rents had priced her out of an apartment and forced her to stay in her car.

With the growing need, more permits have been issued for apartments and multi-unit homes. There were five city-issued building permits for multi-family housing in 2005, 12 in 2006, and 26 in 2007. Still, shortage has driven rents up from $800 just three years ago to $2,000-plus for a typical two bedroom apartment. The shortage of multi-family dwellings partly relates to city planning. Bill Johnson, impact mitigation special service’s energy analyst, notes city general plans need to be adjusted in some areas to allow higher density housing [17]. All of these observations provided insight for the revised planning estimate of population growth in Vernal to support oil shale development.

To understand the urban growth issues facing Vernal and how they influence growth projections, we used the example of Fort McMurray, Alberta, Canada as an example. Fort McMurray, the most geographically proximate city to the oil sands industry, has experienced rapid urban growth driven by the development of the oil sands industry. Officials from Vernal, Utah, are well aware of the growth in Fort McMurray due to the oil sands development. In fact, they organized a visit from Melissa Blake, mayor of Fort McMurray, to learn from her experiences with a town that has grown from 6,000 to approximately 73,000 over a 20-year period. She urged the communities to have a long-term vision and to partner and cooperate with each other. She also suggested the need to weigh population projections carefully, as their growth has outpaced projections every year for the past six years.

The recent growth of Fort McMurray can be observed in Figures 6 and 7. Growth can be seen in several locations but especially in the northwest quadrant. Based on a fringe area development assessment, certain areas around Fort McMurray have been identified as being suitable for future growth. Figure 8 shows these areas in yellow.
Figure 6. Aerial image of Fort McMurray, Canada, collected in 2000.

Figure 7. Aerial image of Fort McMurray, Canada collected in 2007.
Estimating urban growth in Vernal and the Uinta Basin area is informed based on Fort McMurray growth, but it is still not straightforward. Fort McMurray saw population increase from 6,473 in 1971 to 30,772 in 1981, spurred mostly by oil sands development. With the drop in oil prices in the early 1980s, the population remained near 30,000 – 35,000 until the end of the 1990s, when a consistent growth of ~8.5% raised the population to the present population of nearly 80,000. The population in 2005 was approximately 60,000 and the oil sands production rate was 760,000 bbl/day. In 2006, the population was 64,441 and the production rate was 1.13 million bbl/day. While these growth rates are large, they are well below the estimates made by OTA [8] and used recently by [28] and others to estimate water requirements for oil shale development. OTA [8] estimated ~100,000 new residents for a 500,000 bbl/day production rate and nearly 200,000 new residents for a 1 million bbl/day production rate. Based on the Fort McMurray growth, these estimates are high. Vernal and Uinta Basin may grow differently than Fort McMurray, but growth rates nearly two times those observed in Fort McMurray seem unlikely. Combine that with the observation in both Fort McMurray and Vernal that new residents often are temporary, live in multi-family housing, and spend significant periods of time away from the residence suggests the use of a single per capita water use amount for the entire urban population is unreasonable. Temporary residents and those living in multi-family residences use considerably less water than those living in single-family homes [18]. Also, many residents may obtain water from local sources (wells) rather than drawing from engineered municipal infrastructure systems.

Overall, caution must be exercised in making population projections. The Vernal population has already grown to more than 10,000 due to an oil and gas industry boom. Additionally, Fort McMurray Mayor Melissa Blake noted the actual population growth observed in her town was higher than projections [17]. In this case, we are making a projection expressly for estimating water requirements. Based on the data from Fort McMurray, considerations of the likely
demographics, and water use characteristics, we estimated the population growth rate in
the Uinta and Piceance Basin to be 80,000 per 1 million bbl/day production rate. This value
is slightly higher than the Fort McMurray population growth but much lower than growth
estimates used in previous studies and likely provides a more reasonable estimate for the remote
Uinta-Piceance Basin where growth in the region from the industry is not likely to spur
additional growth.

Uinta-Piceance Oil-Yield Estimate
Another key figure to estimate water requirements for future oil shale development is an accurate
estimate of crude oil yield from the oil shale resources. The amount of oil shale present will
dictate the production rate and duration (and thus the water requirement rate and duration). For
this study, a revised estimate of the oil yield from the Uinta and Piceance Basins (Figure 9) is
made using available data for oil shale Isopach layers (the thickness of oil-shale layers), in-place
oil resources (gallon of crude oil per ton of oil shale), and density of oil shale deposits. The three
sources of data used to create the revised estimate are (Table 1): (1) the Utah oil shale database
from the Utah Geological Survey, (2) Fischer assays of oil shale drill cores and rotary cuttings
from Piceance Basin, Colorado, and (3) USGS Miscellaneous Field Study Map and Oil and Gas
Investigation Maps [19].

Data Sources
The Utah Oil-shale Database [20] covers the Uinta basin, Utah. The database provides
coordinates of cores, geological logs, and Isopachs of oil shale zones from the top of the
Mahogany layer to the bottom of the rich oil shale layer. The in-place oil resources (gallon/ton)
are calculated using the average value from the full depth of the oil shale profile in the database.
For the Piceance Basin, the Fischer assays of oil-shale drill cores and rotary cuttings [21] are
used to directly calculate the isopach and in-place oil resources. The USGS Miscellaneous Field
Study Map (MF-958) [19] is used to estimate the in-place oil resources (gallon/ton) of the
Mahogany Outcrop and the Oil and Gas Investigation Maps (OC-132 Sheet 1 to 6) [22] is used
to estimate the Rich (R) and Lean (L) zones Isopach of the Mahogany Outcrop. For both basins,
the oil shale density is assumed to be 2.0 g/cm³ (2.205 short ton/m³) based on the density
measurement of Green River oil shale [23].
Figure 9. The Uinta (yellow) and Piceance (green) Basins are located in eastern Utah and western Colorado, respectively.

Table 1. Data sources used to estimate crude oil yields from Uinta and Piceance Basins.

<table>
<thead>
<tr>
<th>Data Sources</th>
<th>Datasets</th>
</tr>
</thead>
<tbody>
<tr>
<td>Utah Oil-shale database or U.S. Geological Survey Open-File Report 469</td>
<td>Uinta-Isopach, Uinta-In-place Oil Resources</td>
</tr>
<tr>
<td>Fischer assays of oil-shale drill cores and rotary cuttings from the Piceance Basin, or U.S. Geological Survey Open-File Report 98-483</td>
<td>Mahogany-Isopach, Mahogany-In-place Oil Resources</td>
</tr>
<tr>
<td>U.S. Geological Survey Maps MF958</td>
<td>Mahogany-In-place Oil Resources</td>
</tr>
<tr>
<td>Oil Shale Technology [23]</td>
<td>Defined Oil-shale Density =2.0 g/cc</td>
</tr>
</tbody>
</table>

Data Pre-Processing
The Uinta Basin Isopach point features were directly derived from the Utah oil shale database (Figure 10). For the Piceance Basin, the analog USGS maps were scanned, digitized, and georeferenced (Spheroid-based Clark 1866 Geographic Coordinating System) to build the point feature shapefiles. The Piceance Basin (Mahogany Outcrop) Isopachs were digitized as polyline features from [22] including Lean (L1-L5) and Rich (R1-R5) zones and later converted to point features for processing (Figure 11). The in-place oil resources of the Mahogany Outcrop were obtained from the Fischer Assays of oil-shale drill cores and rotary cuttings [21] (Figure 12). Although the spatial reference was geographic, the derived raster (gridded) data were projected into the NAD 1983 UTM projection to facilitate the raster calculations to determine the oil yield estimates.
**Figure 10.** Isopachs (433 points, black) and in-place oil resources (657 points, red) of Uinta Basin study area [20].

**Figure 11.** Point features of Isopach Rich and Lean zones in Piceance Basin Study Area (Mahogany Outcrop).

**Figure 12.** Isopach and in-place oil resources (587 points) of the Piceance Basin Study Area (Mahogany Outcrop) [21].
Data Processing
Standard spline interpolation in ESRI ArcGIS 9.2 was applied to the Uinta Isopach and the in-place oil resources point features to create a gridded continuous dataset (raster image) for the study area. The Piceance (Mahogany) Isopach point feature (Rich and Lean zones) was built by applying “the Feature Vertices to Points Tools” to the Isopach polylines. The point feature (output from the Feature Vertices to Point Tool) was interpolated into the raster images by spline interpolation. Analysis masks were created for the two study areas to guide the processing of the geographic information system to occur only within the designated mask boundary. The masks were set to the extent of the Isopach data, including a 3-km buffer (mask shown in green in Figure 12). The mask areas used were 2,412 mi² (~1.5 mil acres) and 1,530 mi² (~1 mil acres) for the Uinta Basin and the Piceance Basin (Mahogany Outcrop), respectively. The interpolated Isopach and in-place resource datasets were projected to the NAD 1983 UTM projection with grid cell sizes shown in Table 2.

Table 2. Grid cell sizes of interpolated raster images used in oil yield estimates.

<table>
<thead>
<tr>
<th>Raster Images</th>
<th>Data Sources</th>
<th>Grid Cellsize (m x m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Uinta Isopach</td>
<td>USGS Open-File Report 469</td>
<td>285 x 285</td>
</tr>
<tr>
<td>Uinta In-place Oil Resources</td>
<td>USGS Open-File Report 469</td>
<td>795 x 795</td>
</tr>
<tr>
<td>Mahogany Isopach</td>
<td>Rich and Lean Zones OC-132</td>
<td>309 x 309</td>
</tr>
<tr>
<td>Mahogany In-place Oil Resources</td>
<td>In-place oil resources MF958</td>
<td>318 x 318</td>
</tr>
<tr>
<td>Mahogany Isopach</td>
<td>USGS Open-File Report 98-483</td>
<td>299 x 299</td>
</tr>
<tr>
<td>Mahogany In-place Oil Resources</td>
<td>USGS Open-File Report 98-483</td>
<td>318 x 318</td>
</tr>
</tbody>
</table>

Raster images (output from spline interpolation) may contain errors (e.g., negative values) that must be assessed and removed from the analysis. The raster calculations needed to compute the oil yields using standard ESRI ArcGIS 9.2 Map Algebra might fail with negative values. All negative values were assigned a value of zero. An additional filter was then applied to remove in-place oil resources with less than 25 gallons/ton, a value assumed for this analysis to be the threshold for economical oil shale recovery. The crude oil yield within the oil shale layers is estimated using the following function implemented with the Map Algebra function of ESRI ArcGIS 9.2:

\[
\text{Volume of Oil Shale (m}^3\text{)} = \text{Isopach Thickness (m)} \times \text{Grid Cellsize (m}^2\text{)} \quad (1)
\]
\[
\text{Mass of Oil Shale (ton)} = \text{Volume of Oil-shale (m}^3\text{)} \times \text{Density (m}^3\text{ton)} \quad (2)
\]
\[
\text{Crude Oil (gallons)} = \text{Mass of Oil Shale (ton)} \times \text{In-place Oil Resources (gal/ton)} \quad (3)
\]
\[
\text{Crude Oil (barrels)} = \text{Crude Oil (gallon)} / 42 \quad (4)
\]

Figure 13 illustrates the oil yield calculation for the Mahogany Outcrop. The results of crude oil yield estimation are shown in the Figure 14 and Tables 3 and 4.
**Figure 13.** An example of the oil yield calculation of Mahogany Outcrop, Piceance Basin, Colorado (application of equations 1-4).

**Figure 14.** The estimated crude oil yield within the oil-shale Isopach of Uinta and Mahogany Areas (billion barrels) and the distribution of point features within both areas.
Table 3. Comparison of economical crude oil yield estimation from different data sources.

<table>
<thead>
<tr>
<th>Data Sources</th>
<th>Location</th>
<th>Billion Barrels</th>
</tr>
</thead>
<tbody>
<tr>
<td>USGS Open-File Report 98-483</td>
<td>Mahogany Outcrop, Piceance Basin Colorado</td>
<td>124</td>
</tr>
<tr>
<td>Rich and Lean Zones OC-132</td>
<td>Mahogany Outcrop, Piceance Basin Colorado</td>
<td>620</td>
</tr>
<tr>
<td>USGS Open-File Report 469</td>
<td>Uinta Basin, Utah</td>
<td>15</td>
</tr>
<tr>
<td><strong>Total Crude Oil in Both Areas</strong></td>
<td></td>
<td><strong>139-635</strong></td>
</tr>
</tbody>
</table>

Table 4. Estimated crude oil yield of Uinta and Piceance Basins from other studies.

<table>
<thead>
<tr>
<th>Data Sources</th>
<th>Location</th>
<th>Billion Barrels</th>
</tr>
</thead>
<tbody>
<tr>
<td>Trudell et al. [24]</td>
<td>Uinta Basin, Utah (2008 mi²)</td>
<td>214</td>
</tr>
<tr>
<td></td>
<td>Mahogany Outcrop, Piceance Basin Colorado</td>
<td>700</td>
</tr>
<tr>
<td>Cashion [26]</td>
<td>Uinta Basin, Utah</td>
<td>321</td>
</tr>
<tr>
<td>Vanden Berg [27]</td>
<td>Uinta Basin, Utah and Colorado</td>
<td>147</td>
</tr>
</tbody>
</table>

The estimated crude oil yield of the Uinta Basin (Table 3), based on the economical criteria of in-place oil resources of 25 gallons/ton, is 15 billion barrels within 2,412 mi² (1.5 million acres). Compared with other studies (Table 4), this estimate is considerably smaller. Cashion [26] estimated 321 billion barrels, Trudell et al. [24] estimated 214 billion barrels for 2,008 mi² area, and Vanden Berg [27] estimated 147 billion barrels (only assuming 25 gallon/ton threshold). Additional constraints added by Vanden Berg [27] (> 5 feet thick, < 3000 feet of overburden, and no conflicts with existing oil and gas operations) produced an estimate of 77 billion barrels. There is a wide range of estimates due to the uncertainty of the input data and the assumptions made. Our study produced the smallest estimate because our assumptions and area of analysis is the most limiting, which is meant to provide a conservative estimate. The estimated oil yield from the 1.536 mi² (1 million acres) Piceance Basin study area (Mahogany Outcrop) varies from 124 to 620 million barrels, based on the [21] and [19], respectively. For the Piceance Basin, the estimated overall crude oil yield from this study (assuming 25 gallon/ton threshold) is similar to results from the other studies [25,28,29]. Although the area of the Piceance Basin is smaller than the Uinta Basin, the crude oil yield estimate is higher because the Piceance Basin has higher Isopach thickness and in-place oil resources (gallon/ton) [7]. Spatially, the areas of highest potential yield are located at the center of the Mahogany Outcrop in Río Blanco County and in the Uinta Basin in central and eastern Uintah County.

Revised Estimates for Oil Shale Water Demand

Several estimates of water demand for oil shale development in the Uinta-Piceance Basin have previously been developed [7,8]. A thorough analysis by the OTA [8] in 1980 determined a 50,000 bbl/day facility would need 8,500 acre-feet/year of water and a 1 million bbl/day facility would require 170,000 acre-feet/year. One of the more recent studies, completed in 2006 [29], used some of the same information as [8] with the primary difference being an update to the
water requirement for mining and retorting based on technology advancements (1-3 barrels of water /barrel of oil, changed from 2-5 barrels water/barrel of oil). The resulting water requirement estimates (Table 5) were reduced substantially. A major difference in the conclusions of the two studies is the availability of surface waters to provide the necessary water demand. The OTA report [8] concluded that surface water would be sufficient for an oil shale industry developing in the 1980s and reaching 1 million or more bbl/day oil production by 2000. Clearly, that scenario did not occur. Instead, urban development increased massively in the western U.S. and drought conditions highlighted the lower-than-expected average surface flows. Recent studies have considered altered streamflow and water scarcity in the west [7,29]. A study of the capacity of the White River in Colorado to support a 500,000 bbl/day oil shale industry in the Piceance Basin concluded the demands could be met if extractions were limited to 70,000 acre-feet/year and an additional 16,000 acre-feet/year of reservoir capacity was built [29]. Another conclusion from the more recent studies is the need for regional water management to support an oil shale industry producing more than 1 million bbl/day because the spatial and temporal impacts will extend beyond the local area.

Table 5. Previous estimates of oil shale water requirements for selected production rates [7,29].

<table>
<thead>
<tr>
<th>Oil Shale Production Rate (MBbl/day)</th>
<th>Oil Shale Water Requirement (Bbl Water Used/Bbl Oil Produced)</th>
<th>Oil Shale Industry Water Demand (MGD)</th>
<th>Projected Population Growth (People)</th>
<th>Urban Population Water Demand (MGD)</th>
<th>Total New Water Demand (MGD)</th>
<th>Total New Water Demand (MAF)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.5</td>
<td>1-3</td>
<td>21 to 63</td>
<td>96,000</td>
<td>13</td>
<td>34 to 76</td>
<td>0.04 to 0.09</td>
</tr>
<tr>
<td>1</td>
<td>1-3</td>
<td>42 to 126</td>
<td>177,000</td>
<td>24</td>
<td>86 to 150</td>
<td>0.10 to 0.17</td>
</tr>
<tr>
<td>2.5</td>
<td>1-3</td>
<td>105 to 315</td>
<td>433,000</td>
<td>58</td>
<td>163 to 373</td>
<td>0.18 to 0.42</td>
</tr>
</tbody>
</table>

We identified four areas we could address to improve upon previous water requirements estimates [7,8,29]: (1) population projection based on urban growth example, (2) sustainable urban development incorporating water and energy efficiency goals and representing likely demographics of new residents, (3) newer in situ technology and on-site energy generation to extract oil from oil shale resources, and (4) alternative electricity generation technologies. We also sought to incorporate energy demands for water transport and to separate the water demands into oil shale, energy generation, and urban population sectors. These updates seek to make the estimates more accurate and to provide reasonable ranges to the uncertain estimates presented in the past. In addition, by parsing the water demands into sectors, planning and decision-making can be more precise. Water requirements are first estimated for a new base case (using all the information from the previous studies and including energy generation needs for water transport). Then a series of scenarios are analyzed: population growth, sustainable urban development, oil shale extraction technology, and alternative electricity generation. Assessing the effect of the changes to water requirements caused by these scenarios is conducted by comparing the change in water requirements for each scenario to the revised base case and then combining all changes into the “optimistic scenario”. In addition, a “realistic” scenario is presented that includes the most likely scenarios (based on the project team consensus).

Base Case Scenario (Previous Study + Energy for Water Transport)
The energy demand (and associated water requirement) component that has been neglected in most previous studies is the energy required to transport water from source to use. For example, the State Water Project in California delivers 1.3 trillion gallons of water per year over a distance of 621 miles. In order to transport this amount of water, 12,400,000 MWh per year are required [30]. In China, 3.7 trillion gallons of water is transported over a distance of 683 miles requiring 5,000,000 MWh per year [31]. Although China delivers nearly three times more water over a similar distance, their transportation process requires less energy because the lift constraints are smaller. The topographic and geographical characteristics over the transport area are important. Therefore, it is critical for the spatial distribution of water sources and use locations to be identified prior to conducting an energy demand analysis. While this information is unknown, a set of assumptions can be made to produce a rough estimate of this energy demand component for the Uinta and Piceance Basins. First, one water source identified in previous studies that could supply oil shale operations in Utah and Colorado is the White River [29,32]. A conservative estimate of the distance from possible storage or diversion locations to potential oil shale extraction locations is 100 miles. The energy needed to transport water from a source to the urban population centers (e.g., Vernal, Utah and Grand Junction, Colorado) is assumed to be similar. The energy requirement for water transport in Utah is currently being determined [33]. Consequently, the outdated unit value for California (5.92 (mil kWh/day) per (MGD/mile)) must be used as a conservative estimate (1MWh/MGD).

Population Growth Scenario
Previous studies have based urban water and energy needs on estimates of population growth from OTA [8]. However, based on the analysis of the Fort McMurray growth trend (described above), an updated population increase of 80,000 for a 1 million bbl/day industry (40,000 for 500,000 bbl/day production and 200,000 for a 2.5 million bbl/day production) was used.

Oil Shale Extraction Technology Scenario
Advances to technologies are reducing the amount of water required for extraction of oil shale. Water is required to develop oil shale for power generation (in situ heating processes), retorting, refining, reclamation, dust control and other on-site demands. OTA (1980) [8] estimated 2-5 barrels of water to produce 1 barrel of oil, the U.S. Water Resources Council (1981) estimated 3 barrels of water per barrel of oil, and Bartis et al. (2005) [7] estimated 1-3 barrels of water to produce 1 barrel of oil. These estimates all include both on-site and off-site water requirements. It is clear that reliable estimates of water requirements will not be available until the technology reaches the scale-up and confirmation stage [7]. Further, these water budget estimates do not account for the potentially large quantities of water produced during extraction and processing, which may be treated and reused. For our revised estimates, we retained the range of 1-3 barrels of water per barrel of oil from [7] (except for the scenario of advances to oil shale extraction technologies described below).

An important consideration that we investigated in this study was separating on-site water requirements and off-site water requirements (for energy generation) to provide greater precision for future water management planning. To estimate the on-site water requirement range, we started with a conservative estimate from Gleick [30] of 2 barrels water used on-site per barrel of oil produced. The low end for on-site will be zero water required. This scenario may be possible if emerging in situ processing techniques that do not require copious amounts of steam/water are
combined substantial water reuse. The high end of the range for off-site water requirements follows from previous estimates of water demand for energy generation. Past experiments with the Shell ICP technology used 15 to 25 boreholes per square acre with an electric heater at each borehole to heat the oil shale oil shale up to 650-700°F for 2-3 years. Shell estimated this in-situ technique would require 250-300 kilowatt-hours (kWh) of electrical energy to extract 1 barrel of oil [7]. However, recent research developments within Shell and the experiences in the Alberta oil sands indicate energy generation will likely be provided by natural gas-fired facilities. Therefore, the low end of the off-site energy requirements will be no electric energy. The water requirement for off-site energy requirement is estimated based on the energy generation technology chosen and is described below. The high and low estimates provide the range of water requirements that can be used for planning.

Developing the water demand estimates by separating the on-site and off-site water requirements did not change the overall water demand estimates we sought for this study; therefore, we did not include the results in this report. They are relevant for the next phase of our work, which is to refine the water estimates temporally and spatially to provide more useful information for water development planners and water managers.

Sustainable Urban Development Scenario
Water consumption in U.S. cities is highly variable. However, much of this variability is based on the range of industrial, institutional, and commercial entities in a city and the wide range of outdoor water use for landscape irrigation. Indoor residential water use is fairly uniform across the U.S. at approximately 70 gallons per capita daily (gpcd). Utah has the reputation as a significant per capita water user, partially because of outdoor water use to irrigate non-native turf grass landscapes. Given that the demographics of population growth in the Uinta and Piceance Basins will likely include a significant number of temporary workers not living in single family homes with yards, the per capita water use in Utah (245 gpcd, [18]) and Colorado must be reduced to estimate future urban water use associated with growth in the major cities near to the Uinta-Piceance Basin.

The per capita water use of the urban population associated with oil shale development is based on the average per capita water use in the Salt Lake City, Utah metropolitan area, 180 gpcd for single-family residences and 58 gpcd for multifamily residences [34]. These values can be used to estimate the water requirements given future reductions due to implementation of conservation practices. The State of Utah has a stated goal of reducing water use by 25% [18]. Taking this percent reduction, we can estimate future water use to be 135 gpcd and 43.5 gpcd for single-family and multifamily residents, respectively. We can further reduce the single-family residential value by assuming the new developments are made using low-water use vegetation, which will reduce water use by approximately 35-70% [35]. Using the average water use reduction of 50%, the single-family water use under a sustainable development scenario would be 67 gpcd. An equal mix of single-family and multifamily residents can be assumed for the low end of the range to produce a per capita water demand of 55 gpcd for all population added.

In addition, previous studies based their water and energy demands on current (at that time) use rates. Our analysis will include current rates for the base case and future rates including
conservation, which will provide a more realistic picture of the actual energy and water needs in the future.

Urban growth will also affect energy generation demand. The increased energy demand is estimated for this study using a combination of historical energy use data and projected energy use trends. In 1980, the Utah population was less than 1.5 million. In July 2003, the population was 2.3 million for an annual average increase of 2.1% (Figure 15). The electrical energy usage has also increased from 10,705 million kWh in 1981 to 23,205 million kWh in 2001, representing an annual average increase of 3.8% (Figure 16). Based on these numbers, Utah residential electricity consumption per capita has increased from 2133 kWh/person in 1980 to 2949 kWh/person in 2001, for an annual average increase of 39 kWh/person/year (Figure 17). Using this average annual increase, an estimate of energy consumption in 2025 (17 years has been estimated as the time to fully develop the oil shale industry [8]) is 3885 kWh/person. This value can be viewed as the high end of a range, with the low end 20% less (3108 kWh/person) based on the overall energy efficiency goal for the state of Utah in 2015 [36].

Figure 15. Utah population growth [37].

Figure 16. Electricity consumption in Utah [38].
The water requirement for the increased energy demands to support the oil shale industry and urban growth can be estimated based on the energy generation technology employed. New energy generation capacity will be needed in Western Colorado and Eastern Utah to support the oil and gas industry growth and urban growth. Currently, coal-fired power plants provide approximately 95% of the energy in Utah and 83% of the energy in Colorado. Coal-fired power plants are a reasonable assumption for future power generation to support urban growth in the Uinta-Piceance Basin. In general, coal-fired power plants consume 600 gallons of water per Mega-Watt hour (MWh) of energy produced. The National Renewable Energy Laboratory [38] estimated that in Utah, 570 gallons of water are required to produce one MWh in a coal-fired power plant. We contacted two coal-fired power plants in Utah and their consumptive water use amounts were less (450 gal/MWh and 470 gal/MWh). Therefore, we used 500 gal/MWh to be more consistent with observed water consumption at local coal-fired power generation facilities.

Alternative Electric Power Generation Scenario
One scenario included in the analysis was the use of alternative electric power generation capacity. There is potential to develop wind, solar, geothermal, and hydropower in or near the Uinta and Piceance Basins that could supply the oil shale industry and urban population growth. In fact, one study that considered constructing a reservoir on the White River [32] included an analysis of hydropower generation capability. Coal-fired power plants represent the high end of the range for water demand in this study. The low end is represented as a negligible water requirement to support renewable energy generation (wind, solar, geothermal, and hydropower).

Realistic Scenario
A “realistic” scenario was included based on the most likely combination of the scenarios described above. First, oil shale extraction technological advances (in situ processing) and the use of gas-fired power generation for in situ extraction should reduce the on-site and off-site water requirements substantially. Although water neutrality is used as a scenario above, the more likely scenario is a continued need for water on-site that cannot be provided cost effectively by reuse. It is impossible to estimate this amount until the emerging in situ technologies mature. Even if in situ processes do not require copious amounts of water, other activities at the site will require water. A reasonable expectation is that it will be less than the low end of the range (1 barrel of water per barrel of oil produced) used in previous studies. For the “realistic” scenario, a value of 0.75 barrel of water per barrel of oil is used. We feel the revised population estimates
are more likely than the ones developed in 1980; therefore, they will be used for the “realistic” scenario. Future development is likely to follow more sustainable approaches, although achieving 55 gpcd is not likely. Achieving the 25% reduction is likely, which would be 135 gpcd. The urban energy efficiency goal of 20% reduction is also likely and is included in the “realistic” scenario. Although a transition to alternative energy generation is taking place, the “realistic” scenario will include the more likely case of coal-fired power plants providing electric power.

**Optimistic Scenario**

Finally, to determine the water requirement for a scenario where all identified water saving changes are implemented (reduced urban growth estimates, sustainable urban development, advances to oil shale extraction technology, and alternative electric energy generation), we combined the changes to produce the “optimistic scenario”.

A summary of the scenarios included in the analysis is listed in Table 6. It must be noted that the analysis presented herein is not a life-cycle assessment. The estimates for energy and water requirements are for direct and some indirect requirements that would need to be planned and managed locally. We are not factoring in the water and energy required for maintenance, to manufacture and supply chemicals, to supply food to the urban population, etc. We only consider the water requirements in the region due to activities in the region associated with oil shale development. This is an area in need of further work - to study the life-cycle water-energy demands of the oil shale industry growth.
Table 6. Scenarios for future oil shale development water demands.

<table>
<thead>
<tr>
<th>Case</th>
<th>Conditions</th>
</tr>
</thead>
</table>
| 1. Base Scenario (following [7,8,29]) | *Population Increase*: 96,000/500,000 bbl oil, 177,000/1 mil bbl oil, 433,000/2.5 mil bbl oil  
*Water Demand – Oil Shale*: 1 to 3 bbl water/bbl oil  
*Water Demand – Urban*: 135 gpcd  
*Energy Demand – Oil Shale*: included above  
*Energy Demand – Urban*: 3885 kWh/person  
*Energy Demand – Water Transport*: 5.92 (mil kWh/day)/(MGD/mi), 100 mi  
*Water Demand – Energy Generation*: 500 gal/MWh  |
| 2. Revised Population Projection Scenario | *Population Increase*: 40,000/500,000 bbl oil, 80,000/1 mil bbl oil, 200,000/2.5 mil bbl oil  
*Water Demand – Oil Shale*: 1 to 3 bbl water/bbl oil  
*Water Demand – Urban*: 135 gpcd  
*Energy Demand – Oil Shale*: included above  
*Energy Demand – Urban*: 3885 kWh/person  
*Energy Demand – Water Transport*: 5.92 (mil kWh/day)/(MGD/mi), 100 mi  
*Water Demand – Energy Generation*: 500 gal/MWh  |
| 3. Sustainable Urban Development Scenario | *Population Increase*: 96,000/500,000 bbl oil, 177,000/1 mil bbl oil, 433,000/2.5 mil bbl oil  
*Water Demand – Oil Shale*: 1 to 3 bbl water/bbl oil  
*Water Demand – Urban*: 55 gpcd  
*Energy Demand – Oil Shale*: included above  
*Energy Demand – Urban*: 3108 kWh/person  
*Energy Demand – Water Transport*: 5.92 (mil kWh/day)/(MGD/mi), 100 mi  
*Water Demand – Energy Generation*: 500 gal/MWh  |
| 4. Oil Shale Extraction Technology Advances Scenario | *Population Increase*: 96,000/500,000 bbl oil, 177,000/1 mil bbl oil, 433,000/2.5 mil bbl oil  
*Water Demand – Oil Shale*: No water required  
*Water Demand – Urban*: 135 gpcd  
*Energy Demand – Oil Shale*: No water required  
*Energy Demand – Urban*: 3885 kWh/person  
*Energy Demand – Water Transport*: 5.92 (mil kWh/day)/(MGD/mi), 100 mi  
*Water Demand – Energy Generation*: 500 gal/MWh  |
| 5. Alternative Electric Energy Generation Scenario | *Population Increase*: 96,000/500,000 bbl oil, 177,000/1 mil bbl oil, 433,000/2.5 mil bbl oil  
*Water Demand – Oil Shale*: 1 to 3 bbl water/bbl oil  
*Water Demand – Urban*: 55 gpcd  
*Energy Demand – Oil Shale*: included above  
*Energy Demand – Urban*: 3885 kWh/person  
*Energy Demand – Water Transport*: No water required  
*Water Demand – Energy Generation*: No water required  |
| 6. Realistic Scenario | *Population Increase*: 40,000/500,000 bbl oil, 80,000/1 mil bbl oil, 200,000/2.5 mil bbl oil  
*Water Demand – Oil Shale*: 0.75 bbl water/bbl oil  
*Water Demand – Urban*: 135 gpcd  
*Energy Demand – Oil Shale*: included above  
*Energy Demand – Urban*: 3108 kWh/person  
*Energy Demand – Water Transport*: 5.92 (mil kWh/day)/(MGD/mi), 100 mi  
*Water Demand – Energy Generation*: 500 gal/MWh  |
| 7. Optimistic Scenario | *Population Increase*: 40,000/500,000 bbl oil, 80,000/1 mil bbl oil, 200,000/2.5 mil bbl oil  
*Water Demand – Oil Shale*: No water required  
*Water Demand – Urban*: 55 gpcd  
*Energy Demand – Oil Shale*: No water required  
*Energy Demand – Urban*: 3108 kWh/person  
*Energy Demand – Water Transport*: No water required  
*Water Demand – Energy Generation*: No water required  |

Results

D-25
The results for the 6 scenarios are presented in Tables 7 to 13. Important observations and recommendations based on the results include:

- The water requirements to support energy demand for water transport will be significant as shown by changes in water demand for the Base Scenario (Table 7) compared to previous estimates (Table 5). Nearly 10,000 acre-feet/year of water may be necessary to support electric power energy generation needs to transport the larger quantities of water (for the 1-2.5 million bbl/day operations). Not only is the energy requirement for water transport important for water, but it is also an important consideration for energy and emissions.

- The revised population growth estimates reduce overall water demand by 10,000 to 30,000 acre-feet/year (Table 8). This is a substantial quantity of water that would otherwise need to be supplied by the local water conservancy district.

- Interestingly, the reductions produced by following sustainable urban development water and energy efficiencies (Table 9) are nearly identical to reductions noted for the revised population projections scenario.

- For new oil shale extraction advances that reduce water demand to zero, the total water demand is reduced by 50% (Table 10). This is consistent with the observations of water demand for the Alberta oil sands operations where water demands are substantial. This indicates the potential impact of the oil shale industry seeking water neutrality for on-site and off-site water demands is great. **Water neutrality may be feasible through a combination of demand and supply side management actions.**

- Using alternative electric energy generation technologies (e.g., solar, wind, etc.) that do not require significant amounts of water will have a small impact (<5,000 acre-feet/year) for the 500,000 bbl/day operations, but could save more than 10,000 acre-feet/year for the larger oil shale operations (1-2.5 million bbl/day). In addition, the reduced emissions are not factored into this analysis but may be more significant.

- As would be expected, the Optimistic Scenario reduces water to a small storage requirement of less than 12,000 acre-feet/year to support the urban population. The Realistic Scenario indicates planning should account for 120,000 acre-feet/year to support the high end of the oil shale production rate (2.5 million bbl/day).
### Table 7. Water demand summary for Base Case Scenario.

<table>
<thead>
<tr>
<th>Oil Shale Production Rate (MBbl/day)</th>
<th>Oil Shale Water Requirement (Bbl Water Used/Bbl Oil Produced)</th>
<th>Oil Shale Industry Water Demand (MGD)</th>
<th>Projected Population Growth (People)</th>
<th>Urban Population Water Demand (MGD)</th>
<th>Total New Water Demand (MGD)</th>
<th>Total New Water Demand (MAF)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.5</td>
<td>1-3</td>
<td>21 to 63</td>
<td>96,000</td>
<td>13</td>
<td>35 to 79</td>
<td>0.04 to 0.09</td>
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<tr>
<td>1</td>
<td>1-3</td>
<td>42 to 126</td>
<td>177,000</td>
<td>24</td>
<td>69 to 155</td>
<td>0.08 to 0.17</td>
</tr>
<tr>
<td>2.5</td>
<td>1-3</td>
<td>105 to 315</td>
<td>433,000</td>
<td>59</td>
<td>171 to 387</td>
<td>0.19 to 0.43</td>
</tr>
</tbody>
</table>

### Table 8. Water demand summary for Revised Population Projection Scenario.

<table>
<thead>
<tr>
<th>Oil Shale Production Rate (MBbl/day)</th>
<th>Oil Shale Water Requirement (Bbl Water Used/Bbl Oil Produced)</th>
<th>Oil Shale Industry Water Demand (MGD)</th>
<th>Projected Population Growth (People)</th>
<th>Urban Population Water Demand (MGD)</th>
<th>Total New Water Demand (MGD)</th>
<th>Total New Water Demand (MAF)</th>
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<td>0.03 to 0.08</td>
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<td>1-3</td>
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<td>80,000</td>
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<td>0.06 to 0.16</td>
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<tr>
<td>2.5</td>
<td>1-3</td>
<td>105 to 315</td>
<td>200,000</td>
<td>27</td>
<td>137 to 353</td>
<td>0.15 to 0.40</td>
</tr>
</tbody>
</table>

### Table 9. Water demand summary for Sustainable Urban Development Scenario.

<table>
<thead>
<tr>
<th>Oil Shale Production Rate (MBbl/day)</th>
<th>Oil Shale Water Requirement (Bbl Water Used/Bbl Oil Produced)</th>
<th>Oil Shale Industry Water Demand (MGD)</th>
<th>Projected Population Growth (People)</th>
<th>Urban Population Water Demand (MGD)</th>
<th>Total New Water Demand (MGD)</th>
<th>Total New Water Demand (MAF)</th>
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### Table 10. Water demand summary for Oil Shale Extraction Technology Advances Scenario.

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<th>Oil Shale Water Requirement (Bbl Water Used/Bbl Oil Produced)</th>
<th>Oil Shale Industry Water Demand (MGD)</th>
<th>Projected Population Growth (People)</th>
<th>Urban Population Water Demand (MGD)</th>
<th>Total New Water Demand (MGD)</th>
<th>Total New Water Demand (MAF)</th>
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<td>66 to 150</td>
<td>0.07 to 0.17</td>
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<td>1-3</td>
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</table>

Table 12. Water demand summary for Optimistic Scenario.

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<tr>
<th>Oil Shale Production Rate (MBbl/day)</th>
<th>Oil Shale Water Requirement (Bbl Water Used/Bbl Oil Produced)</th>
<th>Oil Shale Industry Water Demand (MGD)</th>
<th>Projected Population Growth (People)</th>
<th>Urban Population Water Demand (MGD)</th>
<th>Total New Water Demand (MGD)</th>
<th>Total New Water Demand (MAF)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.5</td>
<td>0</td>
<td>0</td>
<td>40,000</td>
<td>2</td>
<td>2</td>
<td>0.002</td>
</tr>
<tr>
<td>1</td>
<td>0</td>
<td>0</td>
<td>80,000</td>
<td>4</td>
<td>4</td>
<td>0.005</td>
</tr>
<tr>
<td>2.5</td>
<td>0</td>
<td>0</td>
<td>200,000</td>
<td>59</td>
<td>11</td>
<td>0.012</td>
</tr>
</tbody>
</table>

Table 13. Water demand summary for Realistic Scenario.

<table>
<thead>
<tr>
<th>Oil Shale Production Rate (MBbl/day)</th>
<th>Oil Shale Water Requirement (Bbl Water Used/Bbl Oil Produced)</th>
<th>Oil Shale Industry Water Demand (MGD)</th>
<th>Projected Population Growth (People)</th>
<th>Urban Population Water Demand (MGD)</th>
<th>Total New Water Demand (MGD)</th>
<th>Total New Water Demand (MAF)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.5</td>
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<td>5</td>
<td>22</td>
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</tr>
<tr>
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<td>0.75</td>
<td>32</td>
<td>80,000</td>
<td>11</td>
<td>44</td>
<td>0.05</td>
</tr>
<tr>
<td>2.5</td>
<td>0.75</td>
<td>79</td>
<td>200,000</td>
<td>27</td>
<td>110</td>
<td>0.12</td>
</tr>
</tbody>
</table>

The oil shale extraction and processing water requirements (including energy generation water requirements) are approximately 80% or more of the total water demand. Although the other actions (sustainable development, alternative energy, etc.) can save tens of thousands of acre-feet of water per year (and are relatively low cost measures with significant additional benefits), the highest return can be gained by seeking improvements to oil shale extraction and processing that reduce water demands. The goal should be to seek water neutrality for the oil shale operations. Overall, the results of this analysis suggest water planning for oil shale development should include 32,000 acre-feet/year to support potential urban population growth meeting Utah’s water efficiency goals. Water planning should also include approximately 90,000 acre-feet/year for oil shale operations (2.5 million bbl/day), assuming industrial processes minimize water use to 0.75 barrels of water/barrel of oil. The next step of the water management analysis is to identify possible water sources and analyze their ability to provide these amounts under different climate scenarios. A conceptual framework to conduct this study is described in the next section.
Task 3. Conceptual Approach to Water Availability Assessment

Given the water requirements estimates described above, the next step is to determine if the water is available. Hence, a conceptual approach to determine the availability of water was devised. The conceptual approach begins by considering the water demand in the three sectors (urban, energy, and oil shale industry) and incorporating recycle to quantify the amount available that can be treated and reused (Figure 18). The conceptual model of the system must be populated with quantities of flow and amount of reuse (based on cost) to determine the potential for water reuse to reduce the water requirements. The revised estimates of new water and reused water must then be incorporated into a water management model for the region to determine if there is enough water (in existing water rights as the basin is currently closed to new appropriation) to supply the demands. A previously identified possible source of water to support oil shale operations (and energy development in general) in Utah and Colorado is the White River. Reservoirs have been proposed for both Colorado and Utah, but the hydrologic studies to determine required storage capacities and the feasibility given current uses are based on analyses performed in the 1970s [32]. These analyses must be updated to determine the feasibility of the reservoirs given new estimates of water requirements, more streamflow records, and the possibility of climate change impacting surface flows in the river.

![Figure 18. Conceptual diagram of a water demand, treatment, and reuse system for the three sectors of water demand.](image)

The analyses of water availability can be performed with a water management model based on a mass balance of flows and withdraws from a water body (the White River). The proposed model for this analysis will include existing water rights information, the proposed reservoirs in Colorado and Utah, and the projected demands for urban population, energy generation, and energy development (including oil shale). A conceptual illustration of the water management...
model is shown in Figure 19. To implement this conceptual approach, flow data must be acquired, the existing water rights must be determined from the Utah Division of Water Rights, the water management model must be built, instream flow requirements must be defined based on habitat needs, climate change flow modifications must be estimated, and the range of water demands must be incorporated into scenarios for the study. A long-term analysis using historical streamflow records will then be conducted to determine the performance of the reservoir and optimize its size. In addition, the ability of the White River under different climate, use, and reservoir design scenarios to meet the water demands and maintain instream flows can be determined.

**Summary**

The outcomes of this research project were a collection of geospatial data, reports and papers related to water resources and unconventional oil development, a range of updated estimates for water requirements for oil shale development, and a conceptual approach to determining water availability and planning for water resources development to support oil shale industry growth. Updated estimates of water requirements cover a set of feasible scenarios ranging from past conditions (430,000 acre-feet/year to support a 2.5 million bbl/day operation) to an optimistic scenario (12,000 acre-feet/year to support a 2.5 million bbl/day operation). The estimate based on past conditions would be a significant challenge and cost to supply, whereas the optimistic estimate would be reasonable and a relatively small cost to develop. A realistic scenario developed by the project team was found to require 120,000 acre-feet/year to support a 2.5 million bbl/day operation. While large, this quantity of water is feasible given existing water rights on the White River. A conceptual modeling approach was outlined to determine if the range of water requirements could be provided by the White River system. The next steps were briefly described.
Figure 19. Diagram of White River water management modeling framework [32].

This initial research indicated the need for additional work. Specifically, the following are recommended as extensions of this work:

- Improved demand estimates with spatial and temporal resolution to permit precise water development planning to be performed
- Determination of infrastructure needs and life-cycle cost estimates
- Assessment of life-cycle water and energy demands and environmental impacts
- Compilation and assessment of existing water rights in the Uinta Basin
- Compilation of geospatial environmental quality data to establish baseline conditions
• Creation of a water management model to assess infrastructure planning on water in basins
• Creation of surface and groundwater quantity and quality models

Summary of Publications/Presentations Resulting from this Project

References


[34] Utah Department of Natural Resources. (2001). *Identifying residential water use: Survey results and analysis of residential water use for thirteen communities in Utah*. Salt Lake City, UT.


