Final Report

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An Integrated Framework for Treatment and Management of Produced Water
07122-12

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Executive Summary

Contributions from unconventional gas resources to the nation's energy supply have grown significantly over the past 20 years and demand is expected to drive future growth. With an estimated 293 trillion cubic feet (TCF) of technically recoverable gas from gas shale, coal seams, and tight sands in the lower 48 states, the resources are available to meet future demand. In order to meet this demand, solutions that reduce the amount of water produced are needed.

For proper gas well development in coalbeds water must be pumped out of the formation (dewatering) in order to reduce reservoir pressure and allow the methane to desorb. The co-produced water generated during these operations is by far the largest volume byproduct or waste stream associated with gas production. In contrast to conventional oil and gas production, the produced water from a coal bed methane (CBM) well is pumped in large volumes in the early stages of production and is typically at full pump capacity for up to two years. The quantity of water produced during the life of a well can be 1 to 3 bbl/mcf of gas. If an operator cannot sufficiently minimize water management costs, the CBM resource cannot be developed.

Where proper management of produced water cannot be cost effectively accomplished to meet regulations/permits or surface owner requirements, produced water issues can restrict current gas production or intended expansions.

This project developed an integrated guidance framework that linked the composition of produced waters to beneficial use applications and identified the most cost-efficient, most environmentally sound, and most beneficial strategies for management and treatment of produced water from CBM and gas shale operations by taking into account the conditions in place in the field (http://aqwatec.mines.edu/produced_water/). This was accomplished by cost-benefit analyses that considered both technical and non-technical factors.

This site-specific approach identified potential combinations of treatment processes, which can potentially minimize the volume of residual concentrated brines by considering both well-established and emerging desalination technologies. The project brought together gas producers, members of the water treatment industry, regulatory agencies, tribal interests, landowners, agricultural stakeholders and environmental groups to identify solutions to the institutional impediments to beneficial use of treated water. Input from industry, and particularly from environmental groups, was solicited, with suggestions being applied to the development of the integrated framework.

Section 1: Introduction to Project

1.1 Project Overview

The Colorado School of Mines (CSM), in collaboration with the Argonne National Laboratory (ANL) and Kennedy/Jenks (K/J) Consultants, completed a research program entitled *"An Integrated Framework for Treatment and Management of Produced Water."* The main result of this project was the development of a decision framework to facilitate the evaluation of options for beneficial reuse of produced water. This report describes the Produced Water Treatment and Beneficial Use Screening Tool (Screening Tool) developed to provide the decision framework for assessing opportunities for the treatment and management of produced water.

1.1.1 Background

Contributions to the nation's energy supply from unconventional gas resources, including gas shale, coal seams, and tight sands, have grown significantly during the past 20 years and will play a key role in the nation's energy portfolio in the future. For proper gas well development in coalbeds and gas shales, water must be pumped out of the formation (dewatering) in order to reduce the hydrostatic head or reservoir pressure and allow the methane to desorb. The co-produced water generated during these operations is by far the largest volume byproduct or waste stream associated with gas production. Where proper management of produced water cannot be cost effectively accomplished to meet regulations and/or permits or even surface owner requirements, the intended production of water can restrict current gas production or intended expansions.

Permitting and landowner requirements often leave only two of the options: injection or treatment and discharge. Treatment/discharge is typically the most likely method to maintain the water in the surface water cycle for potential beneficial use. Improved methods are needed of treating and handling produced water that result in sustainable beneficial use or re-injection into the subsurface at a cost that does not impede development of the associated gas resources. While produced water can provide a new source of water for communities, irrigation, and industries especially in the arid west, beneficial use of produced water still faces significant technical, economic, environmental, legal, and institutional impediments.

1.1.2 Project Goal

The management and treatment of produced water has the potential to substantially reduce the overall costs and enhance gas recovery and economic viability (and longevity) of coalbed methane (CBM) and gas shale fields while minimizing potential environmental impacts. This project focused on opportunities for the beneficial use of produced water.

The techniques and methods developed during this study provide needed guidance to the industry in selecting the most cost-efficient management and treatment strategies for handling produced water by considering the site-specific conditions of CBM and gas shale operations. Through cost-benefit analyses and life-cycle analyses, this approach can help to promote more cost-efficient treatment technologies resulting in smaller brine volumes by considering well established as well as emerging desalination technologies, aid in developing strategies to manage and dispose brine streams, and highlight beneficial use scenarios. The results of this research study provides a technically sound, objective integrated framework to identify, quantify, evaluate and communicate both the extraordinary challenges and opportunities posed by the management of produced water in the arid west.

1.1.3 Project Team

The project was directed by Professor Jörg Drewes (CSM) with the following principal investigators: Professors Tzahi Cath and Pei Xu (CSM), John Veil and Dr. Seth Snyder (ANL), and Jim Graydon (K/J Consultants). The project team is supported by key personnel: Dr. Jean Debroux and Dr. Larry Leong, K/J Consultants; Dr. Bob Raucher, Stratus Consulting; Dr. Dean Heil and graduate students at CSM; Dr. Wayne Buschman, Eltron Research and Development; Dr. Jeff Cline, Cline Energy Consultants; and Dr. Dave Stewart, Stewart Environmental.

1.1.4 Stakeholder Involvement

1.1.4.1 Industry Advisory Council (IAC)

The IAC is comprised of industry professionals representing major gas producers. The IAC has been engaged throughout the project through teleconferences and workshops to review and guide the project.

1.1.4.2 Stakeholder Advisory Council (SAC)

The SAC includes water industry professionals, regulatory agencies, tribal interests, landowners, agricultural stakeholders, and environmental groups. The SAC met with the project team at various workshops to address key issues and identify solutions to the institutional impediments to beneficial use and to improve treatment, handling and re-use of produced water from unconventional gas operations.

1.2 Produced Water Overview

1.2.1 What is Produced Water?

Produced water is a byproduct of oil and gas exploration and production, it is generated in large volumes, and it plays a significant factor in the profitability of oil and gas production wells.

Produced water is water trapped in underground formations that is brought to the surface during oil and gas exploration and production. In traditional oil and gas wells, produced water is brought to the surface along with oil or gas. In CBM production, wells are drilled into coal seams, and the water located there is pumped to the surface in order to allow gas to release from the coal seams. Because the water has been in contact with the hydrocarbon-bearing formation for centuries, it has some of the chemical characteristics of the formation and the hydrocarbon itself. It may include water from the reservoir, water injected into the formation, and any chemicals added during the drilling, production, and treatment processes. Produced water can also be called "brine", "saltwater", or "formation water."

The physical and chemical properties of produced water vary considerably depending on the geographic location of the field, the geological formation from which it comes, and the type of hydrocarbon product being produced. Produced water properties and volume can even vary throughout the lifetime of a reservoir.

The major constituents of interest in produced water are:

- ***Salt content:*** Salt content can be expressed as salinity, total dissolved solids, or electrical conductivity. The salt content in produced water varies widely, from nearly freshwater to salt levels up to ten times higher than seawater.

- ***Oil and grease:*** Oil and grease is not an individual chemical. Rather, the term "oil and grease" refers to a common test method that measures many types of organic chemicals that collectively lend an "oily" property to the water.
- ***Various inorganic and organic chemicals:*** These chemicals are found naturally in the formation, are transferred to the water through long-term contact with the hydrocarbon, or are chemical additives used during drilling and operation of the well. The presence of specific chemicals and the concentrations of those chemicals vary widely among different produced water samples.
- ***Naturally occurring radioactive material* (NORM):** Some of the formations holding oil and gas have small concentrations of natural radioactivity. Low levels of the radioactivity can be transferred into produced water. Generally, the radiation levels in produced water are very low and pose no risk. However, scale from pipes and sludge from tanks holding produced water can concentrate NORM.

Most produced waters need some form of treatment before it can be used. The levels of specific constituents found in a particular produced water sample and the desired type of reuse will determine the types of treatment that are necessary and available.

1.2.2 How Much Produced Water is Generated?

Produced water is by far the largest volume byproduct stream associated with oil and gas exploration and production. Approximately 21 billion bbl (barrels; 1 bbl = 42 U.S. gallons) of produced water are generated each year in the United States from about 900,000 wells. This is equivalent to a volume of 2.4 billion gallons per day. Within the five Rocky Mountain States that are the focus of this project (Colorado, Montana, New Mexico, Utah, and Wyoming), approximately 430 million gallons of produced water are generated each day.

To put this volume into perspective, the Denver Water Agency, which supplies drinking water to the about 1.3 million customers, operates three traditional water treatment plants and one recycled water treatment plant. The combined total capacity of those plants is approximately 745 million gallons per day.

1.2.3 Why is Produced Water Important to the Oil and Gas Industry?

The cost of managing produced water is a significant factor in the profitability of oil and gas production. The total cost (ranging from less that $0.01/bbl to more than $5/bbl) includes:

- The cost of constructing treatment and disposal facilities, including equipment acquisitions;
- The cost of operating those facilities, including chemical additives and utilities;
- The cost of managing any residuals or byproducts resulting from the treatment of produced water;
- Permitting, monitoring, and reporting costs; and
- Transportation costs.

Once the cost of managing produced water exceeds the value of the hydrocarbon produced from the well, the well is usually shut down.

1.3 Potential Beneficial Uses for Produced Water

Beneficial use refers to the use of produced water from an oil or gas well for a secondary purpose that has a positive value. Potential beneficial use options for produced water include potable use and non-potable uses, aquifer recharge storage and recovery, surface water discharge, irrigation, wildlife maintenance and enhancement, and more.

The following sections discuss the source and nature of produced water from CBM, the different beneficial uses of produced water, and the reasons behind current and future beneficial use of produced water.

1.3.1 What are Beneficial Uses?

Beneficial Use refers to a reasonable quantity of water applied to a non-wasteful use. Potential beneficial use options for produced water include:

- Domestic Potable Use
- Aquifer Recharge Storage and Recovery
- Surface Water Discharge
- Fishery Flows
- Constructed Treatment Wetlands
- Agriculture Irrigation
- Industrial/Commercial Non-Potable Uses
- Livestock Watering
- Impoundments
- Dust Control
- Mining
- Wildlife maintenance and enhancement
- Recreational
- Fire protection
- Preservation of environmental and aesthetic values
- All other uses compatible with the enjoyment of the public waters

The determination of a specific beneficial use depends on federal and state jurisdiction, and the circumstances of each case. For beneficial use of water from CBM production, the related water right issues must also be determined.

1.3.2 Why Beneficial Use?

Large volumes of produced water are pumped to the surface during CBM production throughout the United States, as shown in . Water must be pumped out of the coal layers (referred to as dewatering) in order to reduce the hydrostatic head (i.e., reservoir pressure) and allow the release of methane. The produced water generated during these operations is by far the largest byproduct or waste stream associated with gas production. The quantity of water produced during the life of a well is typically from 1 to 3 barrels of water per thousand cubic feet (bbl/mcf) of gas. Water production is greatest in the early stages of well production, and it diminishes over time.

Produced water is an inextricable part of the natural gas recovery process. If an operator cannot reduce water production rates or sufficiently minimize water management costs, CBM fields cannot be efficiently developed, and a valuable energy resource may be lost or diminished.

The costs of produced water management vary extensively depending on the location, disposal method, the type of waste (quality and quantity), and the extent of competition in the local or regional area. Direct discharge and impoundment/evaporation are the least expensive management options, while commercial hauling of water or brine disposal are the most expensive options for management of produced water.

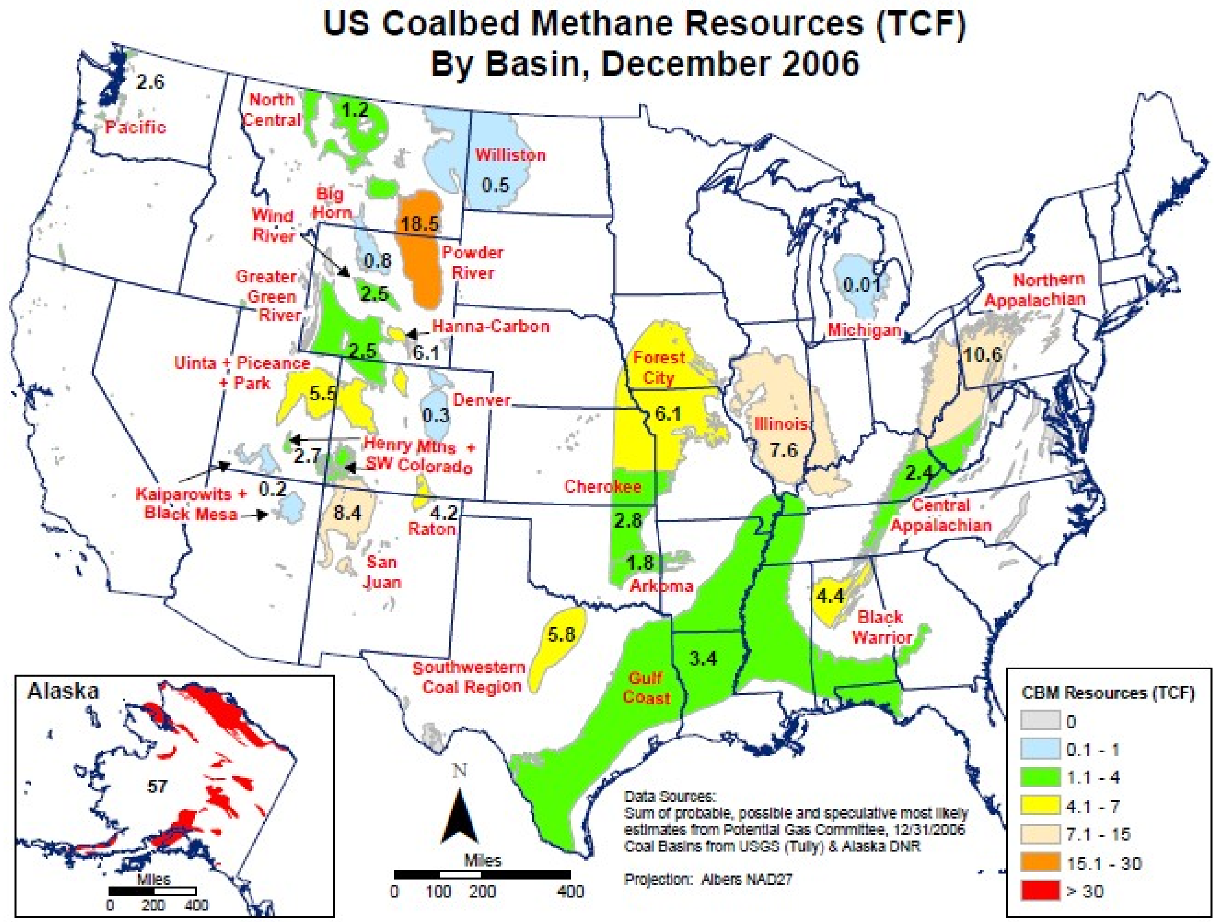


Figure 1-1 US CBM Resources by Basin (trillion cubic feet of natural gas).
Source: Energy Information Administration, http://www.eia.doe.gov/oil_gas/rpd/cbmusa2.pdf.

Today, many freshwater resources in the western United States are fully allocated. Population forecasts suggest that the majority of U.S. population growth by 2020 will occur in western states, representing regions already lacking sufficient and adequate water resources, as shown in Figure 1-2. Increasing water demands associated with energy production and use exacerbate the situation in the West. While this scenario represents enormous challenges, it also provides opportunities for beneficial use of new water resources such as produced water. There are clear needs and strong economic drivers to develop integrative approaches to improve treatment, handling, disposal, and beneficial use of water brought to the surface during production of CBM and other unconventional gas resources.

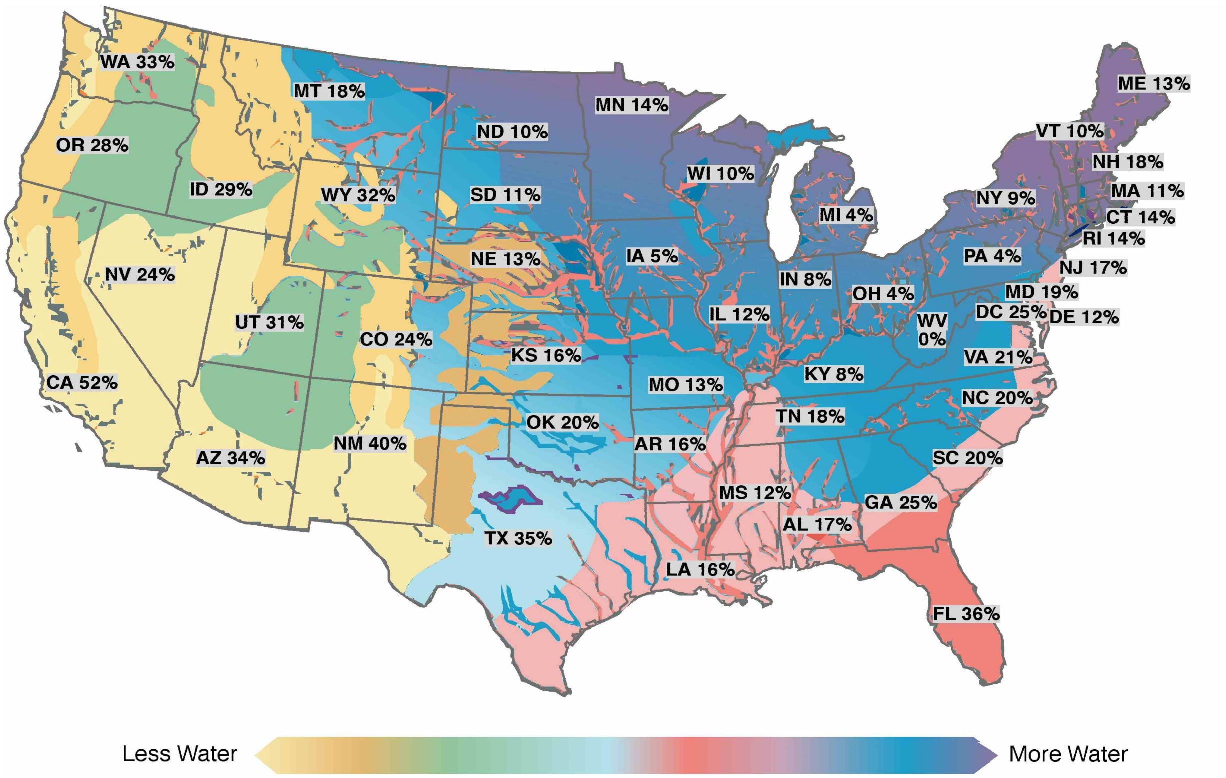


Figure 1-2 Available Water Resources and Projected Population Growth, 2000-2020.
Source: J. Hoffman, S. Forbes, and T. Feeley. 2004. Freshwater needs to meet 2025 electricity generating capacity forecasts. Department of Energy/National Energy Technology Laboratory, Washington, D.C.

1.4 Use of this Document

This document is the final report of this project and it supports the computerized Screening Tool developed to facilitate the evaluation of options for beneficial reuse of produced water. The decision framework can help users, including gas producers, water utilities, governments, and the public to learn about the characteristics of produced water and the major steps, costs, technologies, and environmental issues associated with production of water for beneficial use from CBM produced water. The following sections provide detailed information about how to use the computer model. Case studies were analyzed and documented in a special report. The Case studies use the computerized Tool using a step-by-step approach. The document can be downloaded from the project website (http://aqwatec.mines.edu/produced_water/assessbu/case/)

Additional information is available on the project website http://aqwatec.mines.edu/produced_water/

Section 2: Screening Tool

2.1 Screening Tool Overview

2.1.1 Objective of Screening Tool

The object of the Screening Tool is to facilitate the evaluation of options for beneficial reuse of produced water by assessing opportunities for the treatment and management of produced water.

Selection of processes for water treatment is a complex task and has to consider many parameters that might change over time, including changes in water quality and quantity and economics. Specifically, treatment of produced water is challenging for technical, geographical, and economic reasons. Produced water quality is widely variable, and water may contain contaminants from diverse groups (e.g., dissolved organic and inorganic matter, suspended solids, oil and grease, and dissolved gasses), all of which may interfere with and compromise different water treatment processes.

The management of produced water is equally challenging. Produced water is often generated in remote or isolated gas fields that can at times be inaccessible. This makes it difficult to obtain the necessary energy, supplies (e.g., chemicals, spare parts), and maintenance for treatment systems. It also complicates the transfer and beneficial use of the treated produced water. Above all, the economic implications of the technical, geographic, and environmental restrictions may define the viability of gas-field development.

The Screening Tool may assist professionals and stakeholders in learning and understanding:

- the geographical distribution of quantity and quality of CBM produced water;
- the processes and technologies that are already in use in treatment of CBM produced water;
- new technologies that can potentially be implemented for treatment of produced water; and
- elements included in the cost of treating and using treated CBM produced water.

2.1.2 Study Area

The study area covers five CBM basins in the Rocky Mountain region (Figure 2-1), including:

- Powder River Basin in Montana and Wyoming;
- Raton Basin in Colorado and New Mexico;
- San Juan Basin in Colorado and New Mexico; and

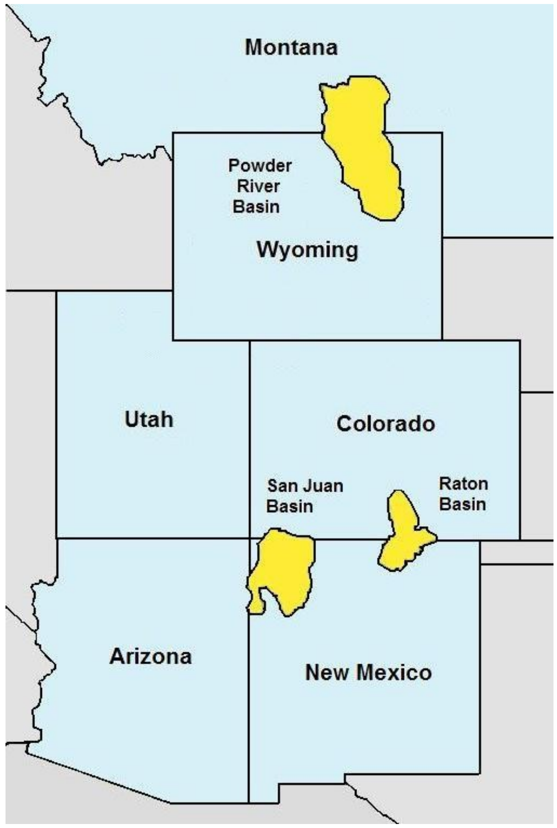


Figure 2-3 Rocky Mountain Region Major CBM Basins

2.1.3 Technical/Software Requirements

The Screening Tool is a macro-enabled Excel workbook. Before downloading the file, please make sure you have Microsoft Excel 2007 or above software installed on your computer. This file was developed and tested on Windows platform, and Macintosh users may experience difficulties working with the program.

2.1.4 Disclaimer

The outputs and results obtained from this integrated decision framework are meant for project screening purposes only as relevant information gathered for these modules are based on limited projects and best engineering judgment. Actual projects will contain details not captured in this analysis that may affect the treatment of produced water, regulatory compliance, project feasibility, and overall cost of the project.

2.2 Screening Tool Modules

The Screening Tool contains four modules: Water Quality Module (WQM), Treatment Selection Module (TSM), Beneficial Use Screening Module (BSM), and Beneficial Use Economic Module (BEM). Each model builds off of information input into the previous module(s) and together the Screening Tool builds a complete picture of utilization of CBM produced water for beneficial use.

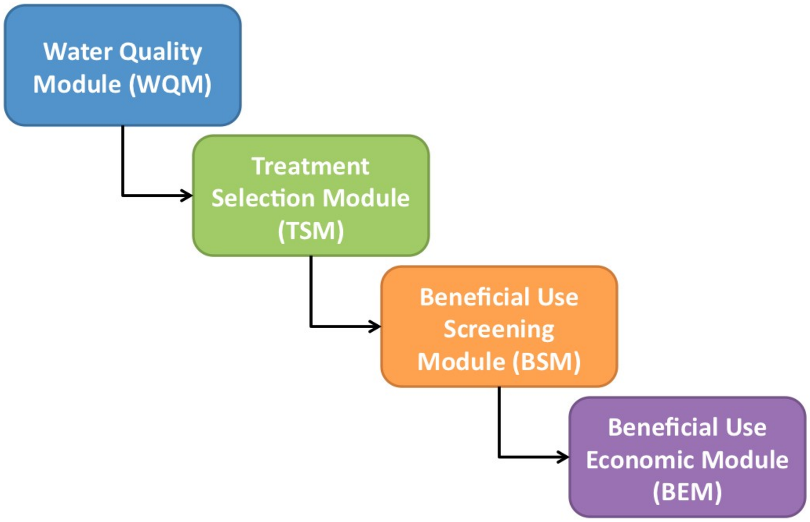


Figure 2-4 Screening Tool Flowchart

2.2.1 Water Quality Module (WQM)

The WQM provides comprehensive produced water quality data for CBM production wells. The module either outputs predicted water quality data for a given location or confirms user input water quality data.

2.2.2 Treatment Selection Module (TSM)

The TSM is designed to suggest treatment trains capable of treating CBM produced water to a quality suitable for a given beneficial use. The TSM generates a report detailing the suggested treatment trains and associated costs and details.

2.2.3 Beneficial Use Screening Module (BSM)

The BSM identifies key issues regarding the feasibility of potential beneficial use projects, including an assessment of the estimated potential value of the produced water and other non-economic benefits. Based on user input, the module screens potential beneficial uses and ranks them qualitatively, indicating those beneficial uses that may be most feasible to guide the user on which uses to focus on for additional assessment.

2.2.4 Beneficial Use Economic Module (BEM)

The BEM provides an planning-level estimate of capital and O&M costs for potential beneficial use projects that is intended to be used for comparative purposes to assess the relative feasibility of different beneficial uses based on the water quality input, treatment technology selection tool output, and other Screening Tool assumptions.

Section 3: Water Quality Module

3.1 Introduction

3.1.1 Purpose of WQM

The purpose of the Water Quality Module is to provide an estimate of water quality constituent concentrations for coalbed methane produced water to design treatment processes to meet requirements for beneficial use. Treatment systems are proposed for beneficial use applications from the estimated parameter concentration data. This module is the first in the four-sequential module outline.

3.1.2 Description of WQM

T he Water Quality Module provides comprehensive produced water quality data for coalbed methane production wells through a composite geochemical database imbedded in the module. The database is comprised of wellhead data from coalbed methane wells across the Rocky Mountain region. Data sources include public records, private historical data from producers, and over 100 sampled well points across major basins. Data are currently available for three major producing basins in the Rocky Mountain Region, including the Powder River, Raton, and San Juan basins (Figure 2-1).

To predict the water quality of wells based on location, the module database is subcategorized by state, producing basin and coal formation. The module can operate with or without user information on water quality. The user designates the pathway the module takes in providing an estimation of constituent concentrations. Using predefined subcategories the module uses the database query to provide estimated water quality constituent concentrations. These concentrations can be reported in a variety of statistical specifications. For instance, the user can designate whether average constituent values or more conservative 95th percentile values are provided from the database. The data provided estimates concentrations for the constituents listed in Table 3-1.

Table 3-1 Water Quality Module Constituent List

Constituents		
▪ Aluminum	▪ Fluoride	▪ Silica (SiO_2)
▪ Alkalinity as $CaCO_3$	▪ Iron	▪ Silver
▪ Arsenic	▪ Lead	▪ Sodium
▪ Barium	▪ Lithium	▪ Sodium Adsorption Ratio (SAR)
▪ Benzene	▪ Magnesium	▪ Strontium
▪ Bicarbonate	▪ Manganese	▪ Sulfate
▪ Boron	▪ Nickel	▪ Temperature
▪ Bromide	▪ Oil and Grease	▪ Toluene
▪ Calcium	▪ pH	▪ Total Dissolved Solids (TDS)
▪ Carbonate	▪ Phosphate	▪ Total Nitrogen (as N)
▪ Chloride	▪ Potassium	▪ Total Organic Carbon (TOC)
▪ Chromium, total	▪ Radioactivity, Gross Alpha	▪ Total Suspended Solids (TSS)
▪ Conductivity	▪ Radioactivity, Gross Beta	▪ Uranium
▪ Copper	▪ Radium-226 + 228	▪ Xylenes (total)
▪ Cyanide, free	▪ Radon 222	▪ Zinc
▪ Ethylbenzene	▪ Selenium	

The constituent list does not include beryllium, antimony, titanium, tin, molybdenum, cadmium, cobalt, and vanadium. These constituents were not detected in sampled wells or concentrations were not available in public and private producer records to validate field samples. The concentrations and occurrence of these constituents varies depending on the location (state), basin, and coal formation from which the water originates. To reduce the differences between the module outputs and observed site variations in water quality, the user inputs should be as specific as possible with regards to the region of production.

The user may also utilize observed water quality data in the module. The user can select the pathway to enter water quality by wellhead. Wellhead water quality data can be entered to the extent of the user availability. The module will suggest concentration values for constituents not included by the user. The module is equipped with the ability to blend wells. Multiple wells can be entered simultaneously, while the user can then select specific wells to combine. The module provides a comparison of the expected database water quality with the user provided data. The user then has the option to designate whether to adapt the user entered data or the WQM values as an output. The output of this module includes the complete constituent list, an adjusted ion balance, and the user input or blended well water quantity flow data. These outputs are used in the following modules as inputs. The module is step up in an easy to follow format with three primary steps. First the user enters the required project information, then has the option to enter additional information to compare user water quality data to the module database, and finally generates the water quality output. The stepwise guide based on the WQM tabs is displayed as Figure 3-5.

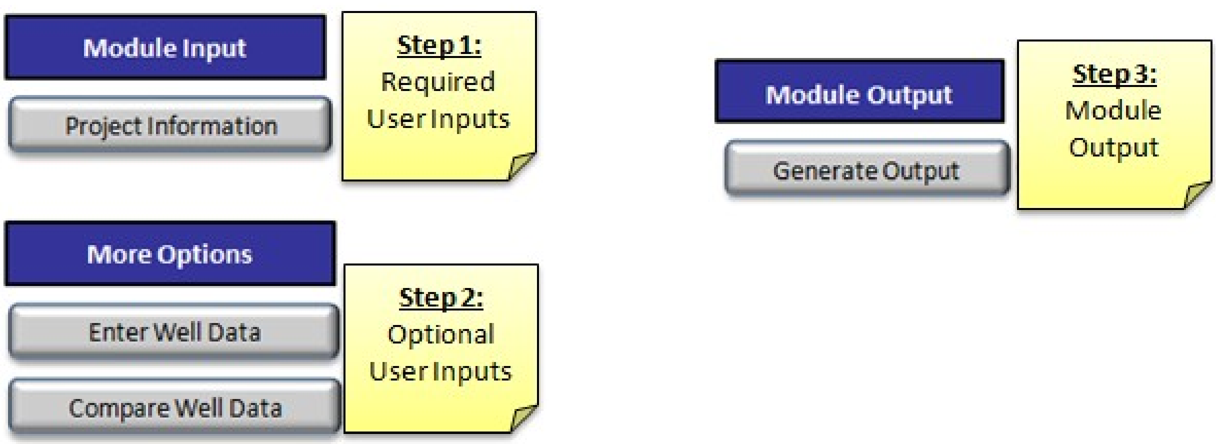


Figure 3-5 Stepwise Guide to the Water Quality Module

3.1.3 Water Quality Glossary

Average Water Flow Rate: The average water flow rate is the water quantity over time expected to occur on average from all the wells contributing to the project.

Basin: Basins refer to geologic hydrocarbon basins producing coalbed methane. Basins available in the module include the Powder River, Raton, and San Juan Basins.

Design Percentile: The design percentile refers to the statistical percentile (average, 50^{th}, 75^{th}, or 95^{th}) where values in the database are selected from. The statistical percentile is an indicator below which a certain percentage of observations occur (i.e., the 75^{th} percentile value is the concentration where 75% of the database concentrations are lower).

Peak Water Flow Rate: The peak water flow rate is the maximum water quantity over time expected to occur from all the wells contributing to the project.

Sodium Adsorption Ratio (SAR): Sodium adsorption ratio (SAR) is a measure of sodicity. It is used as a descriptive parameter to assess the suitability of water for use for irrigation.

State: State in the United States where coalbed methane operations occur. States currently available in the module include Colorado and Wyoming.

Target Formation: The target formation is the geologic coal formation from which water and gas are produced. Target formations are listed for each basin in the dropdown menu.

Total Dissolved Solids (TDS): Total Dissolved Solids (TDS) is the amount of dissolved inorganic and organic constituents in water. TDS is also referred to as salinity. In this module TDS is calculated based on the summation of ions present in the water, however, TDS can also be estimated based on the electrical conductivity of a water sample.

Water Flow Rate Units: There are three water flow rate unit options available, Acre-feet/year (AFY), Barrels/day (Bbl/day), or Million gallons per day (MGD), for selection. The water flow rate units dictate the units in which the average and peak flow rates are entered.

Well Number or Identification: The well number or identification refers to a unique identifier formulated for each well entered into the Well Data template. This identifier can be an API number, a well name, or any combination of characters that are unique to other wells entered.

WQM Database: The WQM database is a composite geochemical database of 47 constituents and parameters present in coalbed methane produced water. The database is comprised of water quality entries from more than 3,000 wellheads obtained from public records, private producer data, and field sampling.

3.1.4 Module Flowchart

The water quality module works between four interactive tabs outside the WQM main menu. The first module tab, “Project Information” includes the only required user inputs in the module. The user then has a choice to enter water quality data or proceed to output without entering additional data. If the user chooses to input additional information the module moves to the “Well Data” module tab, where the complete constituent list is available as a template for user inputs. The user then proceeds to the “Compare Well Data” tab where entered wells are blended to form a single output water quality, water quality information is compared to the database by constituent and the user decides on the data source, WQM or User Data, which will provide values for the “Output” tab. If the user proceeds directly to the “Output” tab the data report will consist solely of the WQM database estimates. The project information, water quality values and flow rate information appear on the “Output” tab where water quality values can be edited for a final time before proceeding to the TSM. A flowchart of the WQM is illustrated in Figure 3-6.

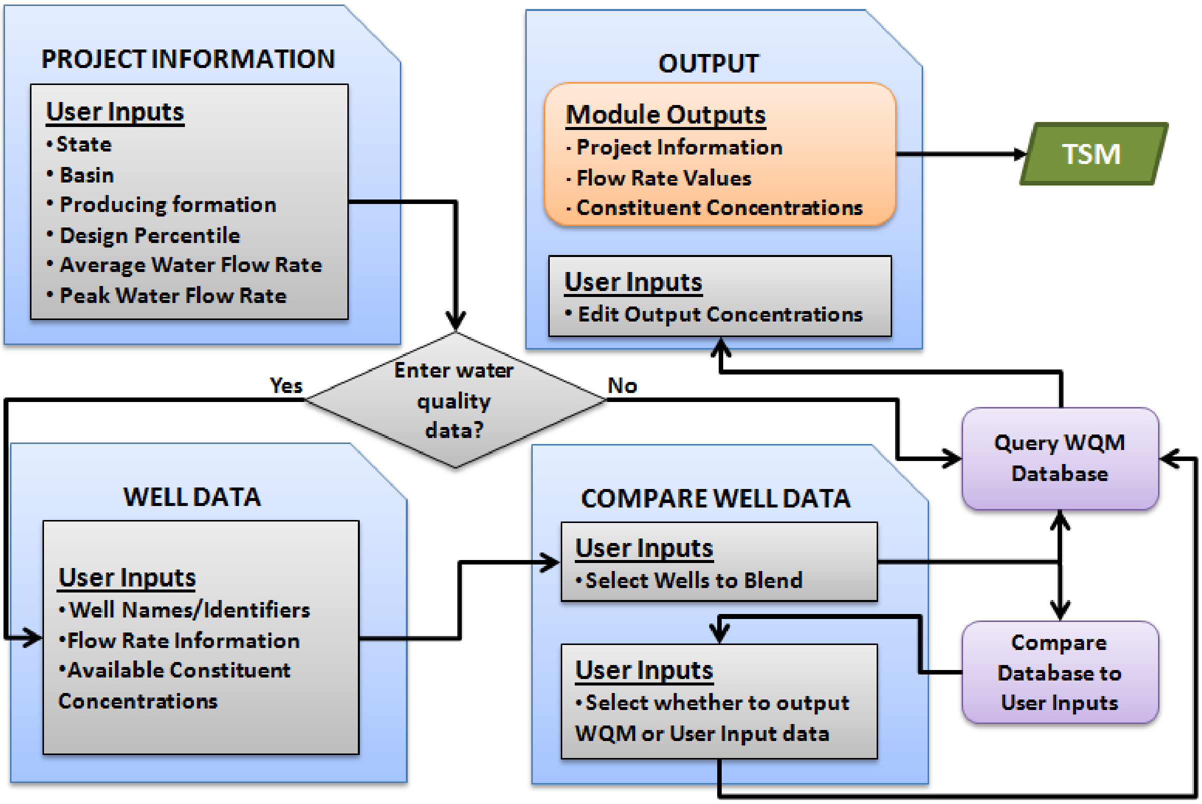


Figure 3-6 WQM Flowchart

3.2 Inputs

The module input tabs are the first interactive tabs the user should visit from the WQM start page. The input tabs include "Project Information" and "Well Data". The Project Information tab contains the required user inputs, while the Well Data tab is optional. Table 3-2 outlines the required and optional user inputs for the WQM.

Table 3-2 Description of WQM Inputs

Input	Unit(s)	Description
Required User Inputs		
State	N/a	User selects project location by state from drop down menu. If the state of operation is not available select other.
Basin	N/a	User selects project location by CBM producing basin from drop down menu. If the basin of interest is not available select other. Available basins include: Powder River Raton San Juan
Target Formation	N/a	User selects target geologic coal formation. Target formations are listed for each basin in the dropdown menu. If the formation is not listed or the well is completed in multiple formations select other or all formations.
Design Percentile	N/a	User selects the design percentile from the drop down menu. The design percentile designates the statistical category the module will draw water quality data from. The more conservative the data the more conservative the treatment process design. The percentiles include: Average 50^{th} percentile 75^{th} percentile 95^{th} percentile (most conservative values)
Water Flow Rate Units	N/a	User selects the water flow rate units to use for entering water quantity information from the drop down menu. A variety of units are provided to facilitate straightforward data entry. The flow rate units include AFY, Bbl/day and MGD.
Average Water Flow Rate	AFY, Bbl/day or MGD	User enters an estimate of the average water flow rate that is likely to be produced as a result of contributions from all the wells in the project design.
Peak Water Flow Rate	AFY, Bbl/day or MGD	User enters an estimate of the peak water flow rate that is likely to occur as a result of contributions from all the wells in the project design.
Optional User Inputs		
Well Number or Identification	N/a	The well number or identification refers to a unique identifier formulated for each well entered into the Well Data template.
Water Quality Constituent Concentrations	Vary	Water quality constituent concentrations are entered as numerical values into the Well Data tab as available by the user. This template does not require the entry of all constituent concentrations. Note the units of entries on the left column following the constituent name.
Select Wells to Blend	N/a	Well identifiers are listed in the Compare Well Data tab and the user selects whether to include the well in the blending tool by selecting yes or no. The user water quality values change in real time as wells are included or removed from the blending tool.
WQM Value	N/a	The water quality data queried from the water quality module database is utilized as the output water quality value for the module.
User Input	N/a	The water quality data calculated from the user well data inputs is utilized as the output water quality value for the module.

Step 1: Project Information or the required module inputs are available mostly as dropdown

menus. The module is amenable to a broad range of user inputs. Users with information limitations in the form of locations or basins of interest may select prepared basins and locations from dropdown menus or select "other" from all dropdown location entries to access the complete database without specific water quality location classifications. The required user inputs from the Project Information tab include general location information such as the basin, the state, target coal formation, the design percentile to control the conservativeness of constituent estimation, and general water flow rate information including units, average and peak flow rates expected for the project. These entries are carried through the module and dictate items such as the treatment system size based on the flow rates, the beneficial use options, and project cost estimate.

At this point the user can elect to enter additional water quality information. To enter additional information the user continues to Step 2, or if not, the user can proceed to the WQM Output directly at this time.

Step 2: Well Data or the optional user inputs are available in the form of a template in the Well Data tab. The template requires the entry of a unique well identified to help the user recognize the well in a later tab. This identifier can be numerical or incorporate letter characters. Additionally the average and peak water flow information must be entered for each well. If the wells contribute equally, then enter the same flow information for each well. Alternatively discharge or collection points can also be entered in this template. The composite water quality and flow data must be entered for each point. Be aware that the overall project flow rate (average and peak) will be a summation of the flow information entered for each well. It should also be noted that the average and peak water flow rate output by the module will be calculated from the wells selected to be included from this template.

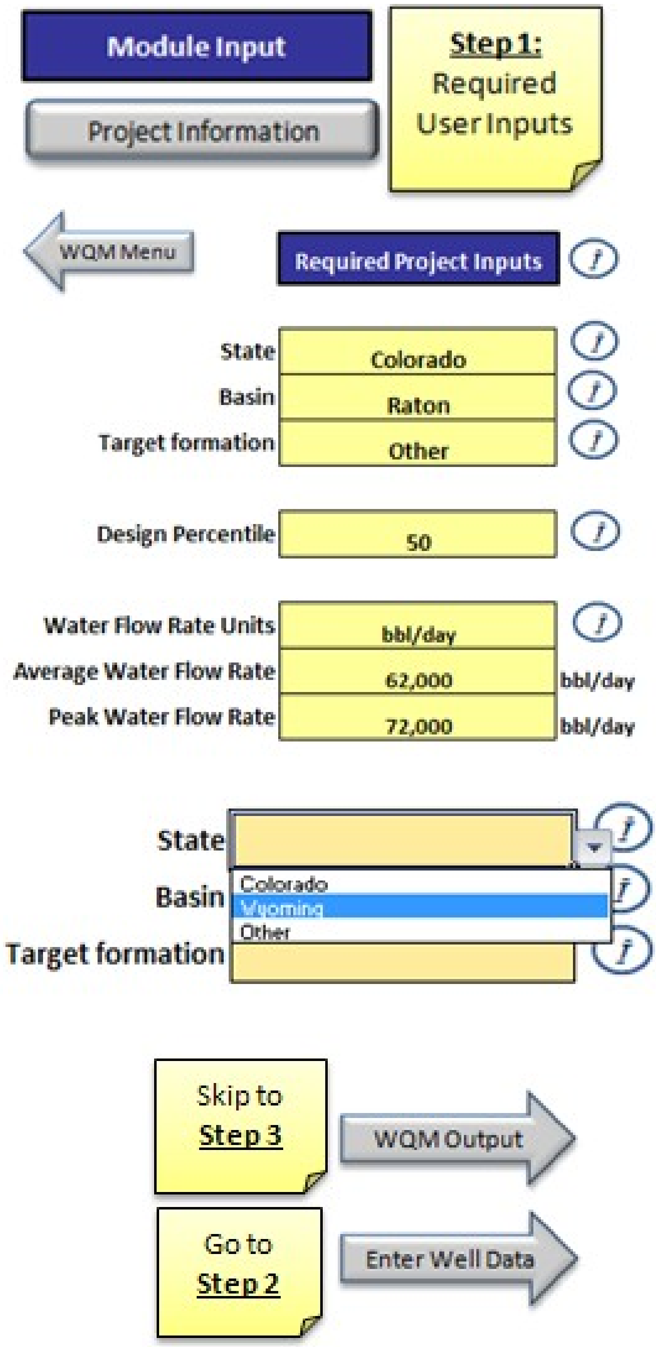
> *Hint: If the user has water quality information for an entire project that is not in the form of individual wells or multiple collection points enter only a single well entry and use the complete average and peak project flows as the individual water flow information.*

The Well Data template includes a list of 47 constituents. The constituent list includes physical parameters, inorganic constituents as metals and non-metals, organic constituents, radionuclides and descriptive parameters such as the sodium adsorption ratio (SAR):

$$SAR = \frac{[\mathrm{Na}^{+}]}{\sqrt{\frac{1}{2}([Ca^{2+}] + [Mg^{2+}])}}$$

In the Well Data template the user can elect to include as many parameters per well as are available. Missing parameters will be supplemented with data from the WQM. If a constituent concentration is non-detect enter zero as the user data value. All entered constituent values are compared to the WQM database to validate that values are observed within the expected range of concentrations for the constituent or between the minimum and maximum observed value in the database. Data assessment is described in the following section.

Step 1, required user inputs, is outlined in Figure 3-7 in the form of a visual user guide. If the user has elected to enter water quality information the procedure for Step 2 follows as a visual description in Figure 3-8.



Step 1: All users must first proceed to the Project Information tab. **Click the Project Information button.**

All users are required to enter the following project information. **From the dropdown menus select the State, Basin, Target Formation, Design Percentile and Water Flow Rate Units.** Finally, the user must enter numerical estimates using the selected water flow rate units. **Enter numerical values for peak and average water flow rates.** These values will define the size of the project treatment system.

All inputs are highlighted by yellow boxes. The dropdown menus contain the only acceptable data

After completing the inputs on the project information page the user has two options. Skip to **Step 3: Continue directly to the WQM output** or continue to **Step 2: Enters water quality information to use as the data for the treatment design.**

Figure 3-7 WQM Step 1: Required User Inputs Guide

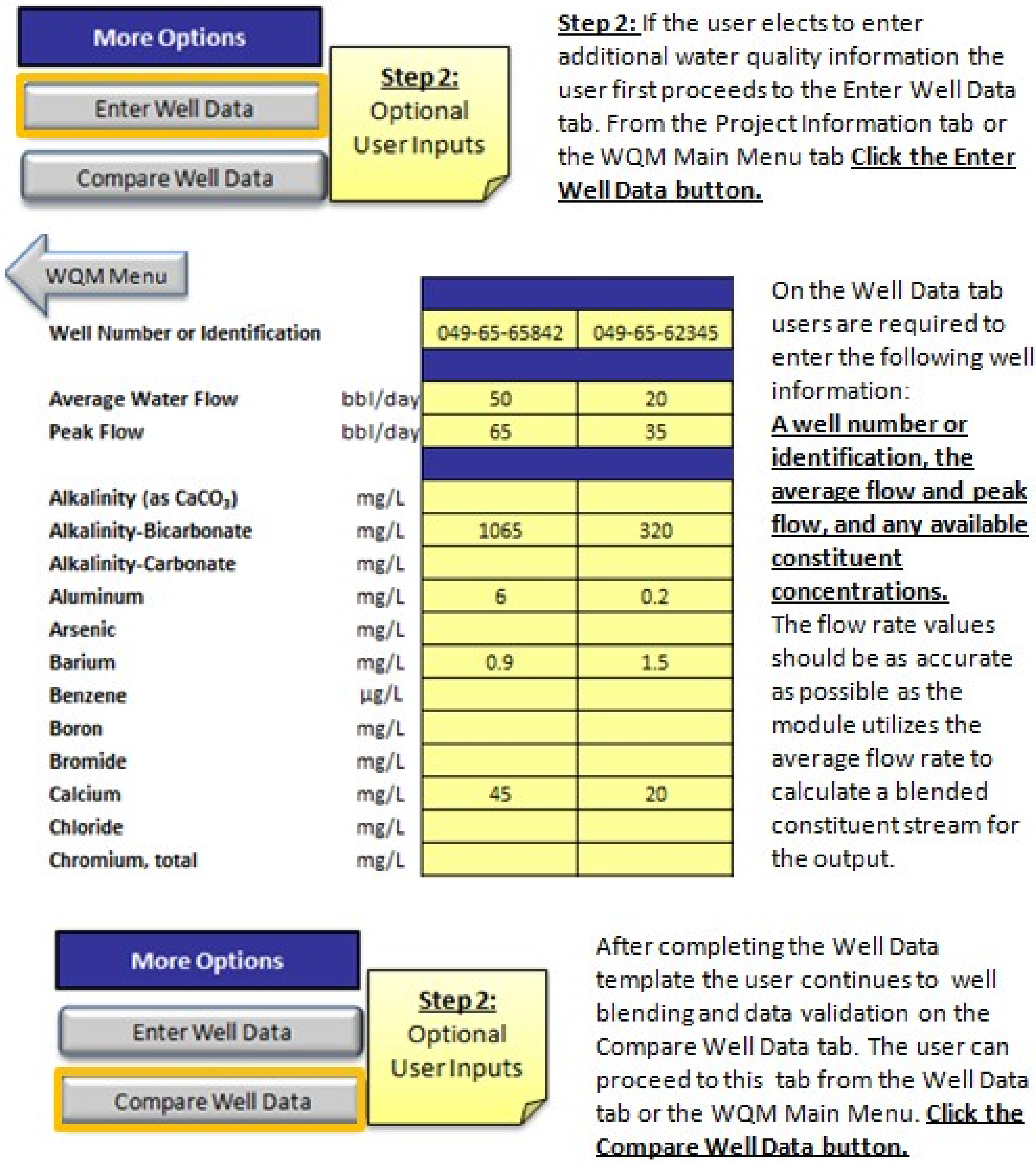


Figure 3-8 WQM Step 2: Optional User Inputs Guide (Part 1)

3.3 Water Quality Selection, Validation, and Calculations

Attributes and functions of the WQM center around the use of a comprehensive constituent database for coalbed methane wells in the Rocky Mountain region. The database includes over 3,000 individual coalbed wellhead data points. Water quality data was obtained from public record, private producer historical databases, and over 100 water samples collected and analyzed by the Colorado School of Mines. The database has comprehensive information for three major producing basins and subsequent target formations. Additional data are also included in the database for other basins, however, the data either lacks complete constituent information or the sample set was not validated by another source (such as private records or field samples). Due to these constraints only the following list of basin (Table 3-3), locations, and formations are included as WQM dropdown menu locations. Table 3-3 describes the data query results from the WQM database for the following user input variations.

Table 3-3 WQM Database Query Results from User Inputs

State	Basin	Formation	WQM Database Query
Colorado	Raton	Raton	Colorado, Raton Basin, Raton Formation only
		Vermejo	Colorado, Raton Basin, Vermejo Formation only
		All Formations or Other	Colorado, Raton Basin, All Formations
	San Juan	Fruitland	Colorado, San Juan, Fruitland Formation only
		All Formations or Other	Colorado, San Juan, All Formations
	Other	Other	Colorado, All Basins, All Formations
Wyoming	Powder River	Anderson	Wyoming, Powder River Basin, Anderson Formation only
		Big George	Wyoming, Powder River Basin, Big George Formation only
		Canyon	Wyoming, Powder River Basin, Canyon Formation only
		Wall	Wyoming, Powder River Basin, Wall Formation only
		Wyodak	Wyoming, Powder River Basin, Wyodak Formation only
		All Formations or Other	Wyoming, Powder River Basin, All Formations
	Other	All Formations or Other	Wyoming, All Basins, All Formations
Other	Other	Other	All States, All Basins, All Formations

When proceeding directly from Step 1 the resulting data in the Output tab reflects the query from the WQM database. The query is based on the user specifications of state, basin, and target formation. The user must return to the project information tab to change these inputs. If the user elected to enter water quality information this database query is reported in the form of a table in the Compare Well Data tab. The Compare Well Data tab is the second part of Step 2 for using the WQM.

Step 2 continued: On the Compare Well Data tab a list of entered well identifiers shows up on the left side of the tab. Next to each well identifier is the option to "Yes" include this well in the dataset or "No" exclude this well from water quality and flow rate calculations. To change the options of wells to include use the dropdown menu to select yes or no. As you change the wells that are included the table on the right hand side of the tab will change in real time to reflect changes to the column "User Input". This table reports the constituent list, WQM Values from the database query and User Input concentrations for the selection of blended wells.

The WQM Values and User Inputs can be compared side by side and in the final column "Select Value" the user selects "WQM Value" or "User Input" from the dropdown menu to select which value will be used in the output. The module identifies User Input values outside the observed range of concentrations, less than the minimum or greater than the maximum database values, by highlighting the text in red. The default is to include all User Inputs as output values. A visual description of the second part of Step 2 is included in Figure 3-9.

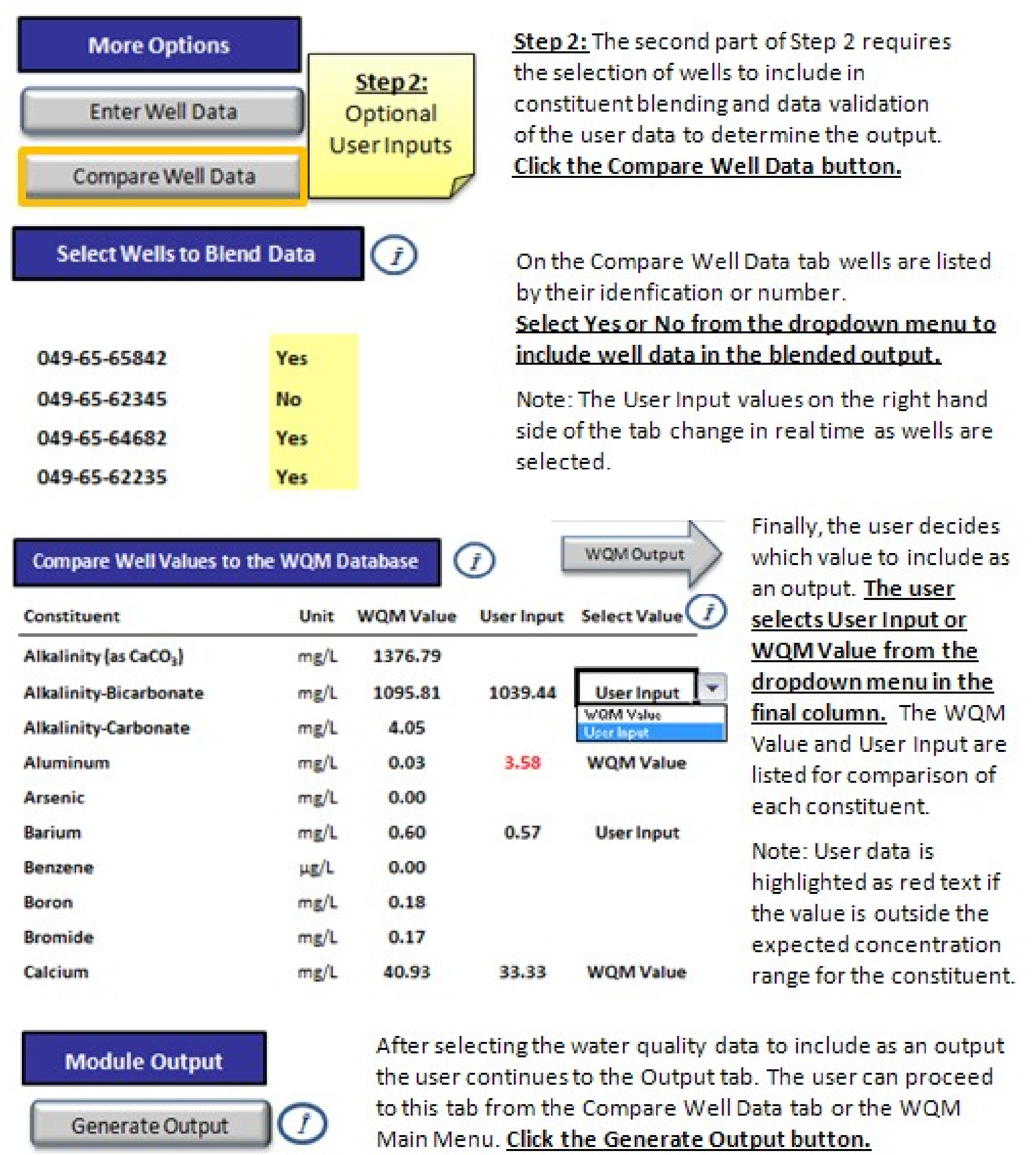


Figure 3-9 WQM Step 2: Optional User Inputs Guide (Part 2)

Prior to the Output tab two additional internal functions are performed by the module. These functions are calculations and modifications to the output data and include an ion balance and parameter calculations. These calculations are described below:

Ion balance: The ion balance adjusts water quality data when the cation-anion discrepancy shifts beyond 15%. This is calculated by summing the milliequivalents per liter of the cations and anions. If the difference between the summations is greater than 15% the module will utilize the ion balance function. The balance works by first identifying the dominate salt in solution (i.e. NaCl or $NaHCO_3$) and the lacking ions (i.e. cations or anions). The balance calculates the remainder or difference between the anions and cations. After calculating the value the balance adds either cations (commonly sodium) or anions (likely bicarbonate or chloride) to the data to adjust the balance to equal one another. The water quality data included for users in the module is balanced within 15%. The ion balance occurs when users input data with a resulting balance above 15% or more commonly when a user enters an additional high value for a single cation or anion (i.e. sodium or bicarbonate), which shifts the cations and anions out of balance.

<u>Total Dissolved Solids (TDS)</u>: TDS is the summation of the dissolved constituents. TDS is calculated from the final output constituent list by the user. This calculated value will override the User Input for this parameter. The user has the option to change the TDS output on the final Output tab before proceeding to the TSM, but this is not recommended because the TSM will recalculate the TDS based on the constituents present before designing treatment. Of the 47 parameters on the constituent list TDS does not include the summation of conductivity, pH, temperature, SAR, oil and grease, radionuclides or total suspended solids (TSS).

$$\text{TDS} = \sum \text{Dissolved Inorganic and Organic Constituents}$$

<u>Sodium Adsorption Ratio (SAR)</u>: SAR is a measure of sodicity. It is used as a descriptive parameter to assess the suitability of water for use for beneficial use opportunities such as irrigation. The SAR is calculated from the output values of sodium, calcium, and magnesium. The output concentrations are converted to milliequivalents per liter to be utilized in the following equation.

$$SAR = \frac{[\text{Output Value} - \text{Na}^{+}]}{\sqrt{\frac{1}{2}\left([\text{Output Value} - \text{Ca}^{2+}] + [\text{Output Value} - \text{Mg}^{2+}]\right)}}$$

This output value is also overridden in the output file by this function. The user has the option to adjust this output on the final output tab before proceeding to the TSM. On the output tab both the TDS and SAR values are highlighted in red to differentiate them as calculated values from the other values output in the constituent list.

3.4 Outputs

<u>Step 3</u>: The final step in the WQM is to proceed to the output tab. Whether the user has entered additional water quality information in Step 2 or proceeded directly from Step 1, the output tab is the culmination of selecting water quality data for use in the TSM. The output screen provides users with a consolidated page of all general user provided data, reference to the outcome of their database survey, and results of their private data augmentation. The WQM output tab is formatted to be easy to print and manipulate before proceeding to the next module. On the output tab constituent values can be edited directly by typing new values. These values are highlighted in yellow boxes and can be returned to the original values using the button in the bottom right corner. Other outputs can be modified by returning to previous tabs. The Outputs and pathways to modify the outputs are included in Table 3-4. After reviewing the output information, the user can send water quality and quantity data to the Treatment Selection Module (TSM) by clicking the Next Module arrow. The Output tab, a guide to modifications, and movement to the TSM are provided with visual representation in Figure 3-10.

Table 3-4 WQM Output Results and Manipulations

Output	Modify Data on Tab	Data Editing Process
Project Information	Project Information	Return to the Project Information tab to alter general project information, location and design percentile
Flow Rates	Project Information or Well Data	Return to the Project Information tab to alter water flow rates or edit individual well flow rates in the Well Data tab
Constituent List	Well Data, Compare Well Data or Output	Return to Well Data to edit individual wells, go to Compare Well Data to select WQM Value or User Input, or edit directly by typing values on the output tab.

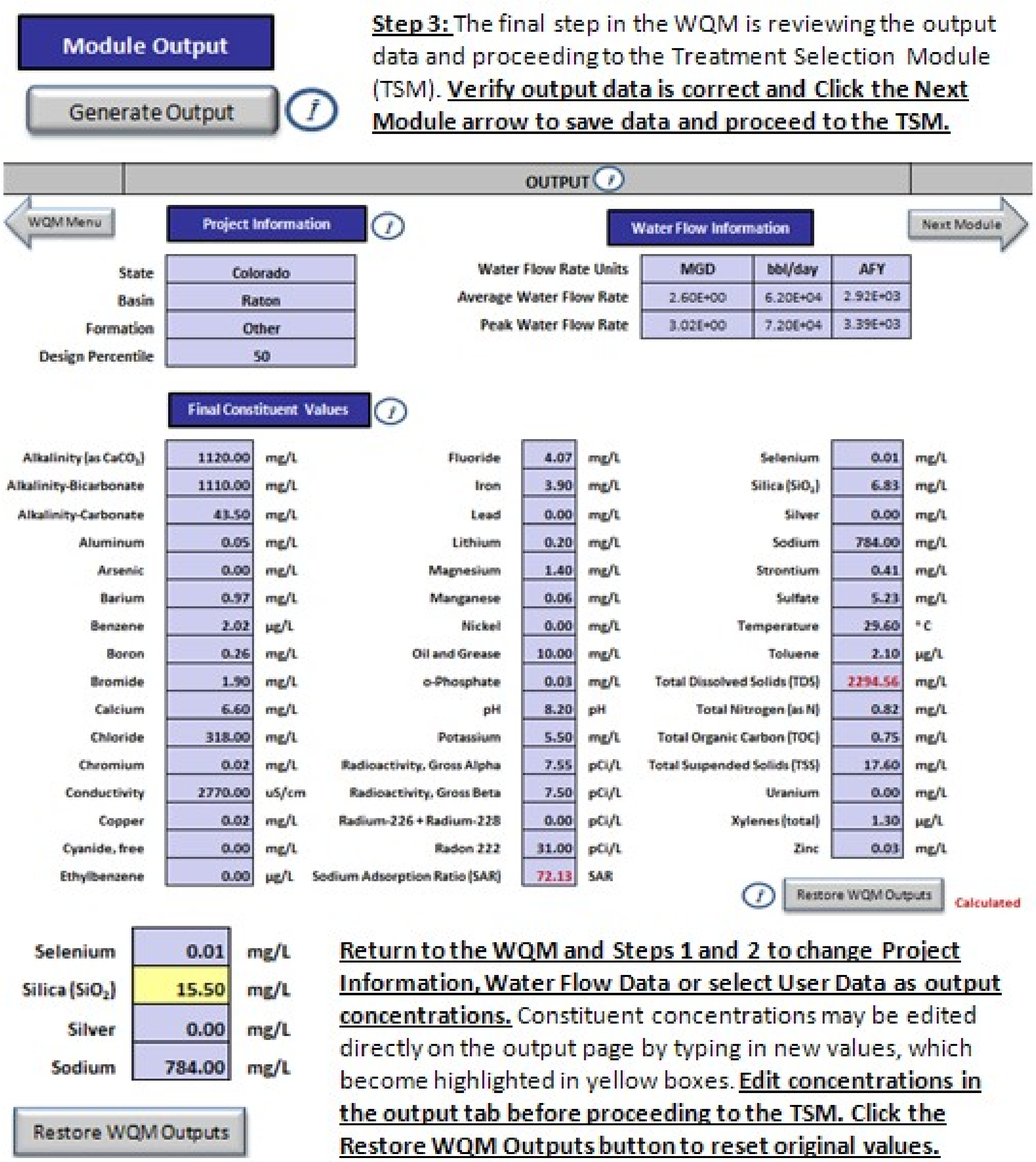


Figure 3-10 WQM Step 3: Final Output Guide

3.5 Nexus with other Modules

3.5.1 Treatment Selection Module

The WQM provides a complete list and estimation of concentrations for 47 parameters and constituents occurring in produced water in CBM production wells. User data from production wells is blended, validated, and augmented by the WQM database. The WQM provides location specific water quality information for input into the TSM. The users must proceed through this module first in order to create or input comprehensive water quality information to properly design a water treatment process that meets predetermined beneficial use requirements.

3.5.2 Beneficial Use Screening Module

The data delivered to the BSM includes the water quantity information in the form of peak and average flow rates. Data is also transferred indirectly from the TSM and includes the best-ranked treatment train for each beneficial use, and the capital cost and energy and chemical demand for these treatment trains.

3.5.3 Beneficial Use Economic Module

The WQM provides inputs for the TSM and BSM but does not directly interact with the Beneficial Use Economic Module (BEM).

Section 4: Treatment Selection Module

4.1 Introduction

4.1.1 Purpose of TSM

The purpose of the Treatment Selection Module (TSM) is to select suitable treatment trains based on water quality, intended use of the treated water (beneficial use) and site conditions as specified by the user. The purpose is also to provide further information on these selected trains (e.g. capital costs, energy consumption, product water quality). The module is not meant to replace an engineering design – it is a broad estimation tool, which suggests some reasonable treatment trains that would meet the user's main requirements.

4.1.2 Description of TSM

Table 4-5 describes the worksheets that comprise the TSM.

Table 4-5 Overview of TSM Worksheets

Worksheet (Tab Name)	User Input Required	Description
Selection Criteria (TSM_selec_crit)	Yes	In this sheet the user inputs selection criteria scores. These scores describe the importance of various characteristics of a treatment process depending on conditions at the site with a five indicating that the item is extremely important and a one indicating that the item is not very important at all. These scores allow the program to prioritize the various treatment trains that are capable of achieving the desired water quality and thereby select the most optimal trains for output to the user. For example if the user has a site where space is freely available they would score 'small footprint' as a 1 because footprint considerations are not very important at such a site. However, if space was limited they would score this as a 5 so that the program would prioritize any treatment processes that required very little space.
Additional Information (TSM_Addt_Input)	Yes	This sheet requests further water quality data regarding bacteria from the user. The program uses this information to select disinfection processes where necessary.
Water Recovery (TSM_Recovery)	Yes	This sheet asks the user for the level of recovery they desire during membrane desalination processes (recovery relates only to membrane processes). When salt is removed from water it is often accomplished with membranes. During membrane treatment water is pushed through a membrane which allows the water molecules to cross but rejects the salt leaving that behind. However, not all the water crosses the membrane but instead some of it remains behinds with the salt forming highly concentrated brine. Recovery refers to how much of the original feedwater crosses the membrane. If the recovery is equal to 70% this means that 70% of the original feed water became the purified product water and 30% remained as part of the brine. The level of recovery possible is limited by the salinity level in the brine because at high enough concentrations salts precipitate out and interfere with whole treatment process. The program takes account of this and warns the user when recovery is too high.

Worksheet (Tab Name)	User Input Required	Description
Water Quality (TSM_WQBU_Data)	No	This sheet is for information only. It provides the user with the water quality data from the WQM and shows a comparison between this and various beneficial use limits or guidelines. If a water quality value is highlighted in red it indicates that the corresponding constituent is above the limit or guideline for that beneficial use and will require treatment. The beneficial use being assessed can be changed using the drop down box at the top of the third column. All the beneficial uses with their guidelines can be viewed by clicking on the box entitled 'see all beneficial use categories and limits'.
Previous Output (TSM_Output)	Yes	This is actually the same sheet as the Output sheet. The button is provided so that the user does not have to rerun the program every time they wish to view their treatment options or move on to the next module. **NOTE:** If any inputs have been changed in the WQM or the TSM these **will not** reflect in the outputs shown when pressing this button. If any changes have been made the user must rerun the TSM by clicking on the RUN button on the TSM Main Menu page.
Output (TSM_Output)	Yes	This sheet pops up automatically after the TSM RUN button has been clicked. The RUN button initiates visual basic code in the background of the program. The code runs through all the various treatments, all the constituents that require treatment and the selection criteria and from these selects optimal treatment trains for each beneficial use. These results (from running the code) are displayed on the output sheet. The user is provided with a number of treatment trains for each beneficial use and needs to select one of these for further assessment in the BSM and BEM modules. The user can also view further information, such as energy consumption and capital costs for each process, by clicking on the **+** buttons in the margins of the page.
Detailed Water Quality (TSM_WQ)	No	This sheet provides the user with the water quality of the product and brine streams. The brine stream will only be relevant where some type of desalination was done. The page also provides the limits or guidelines for the relevant beneficial use and highlights in red any constituents that exceed these limits.

4.1.3 Module Flowchart

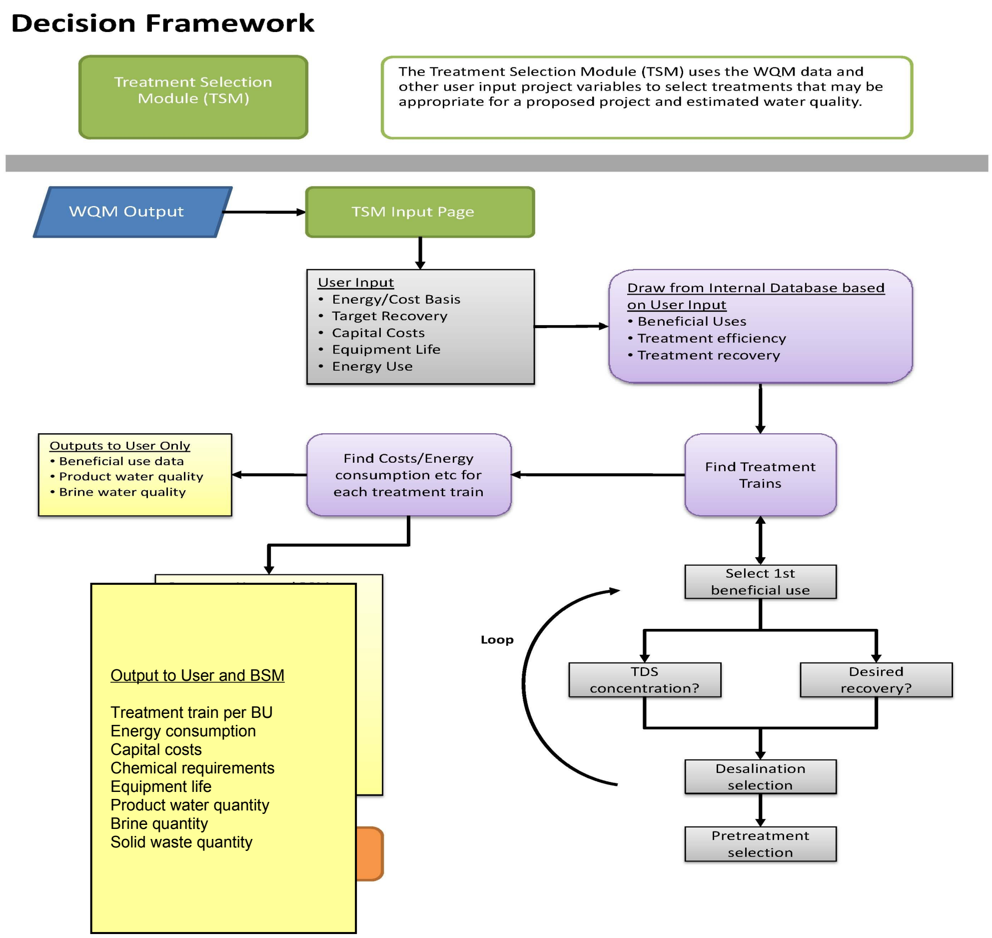


Figure 4-11 TSM Flowchart

4.2 Input

A description of the TSM input requirements is provided in Table 4-6.

Table 4-6 Description of TSM Inputs

Input	Unit(s)	Description
Selection Criteria Scores	N/a	The user enters numbers between 1 and 5 in each of the yellow cells corresponding to each selection criteria. A five indicates that the item is extremely important and a one indicates that the item is not very important at all. For example if the user has a site where space is freely available they would score 'small footprint' as a 1 because footprint considerations are not very important at such a site. However, if space was limited they would score this as a 5 so that the program would prioritize any treatment processes that required very little space.
Bacteria in the Feedwater	HPC/100ml	The user selects between the 3 options (No bacteria, low HPC and high HPC) by selecting the radio button beside that option. HPC stands for Heterotrophic Plate Count. If the user is uncertain of whether there is bacterial contamination they should select high HPC to receive the most conservative estimate of treatment train cost.
Recovery	Percent	The user clicks on the up or down arrows to reduce or increase recovery. The user can also enter the recovery level into the yellow cell directly from their keyboard. The recovery input relates to desalination options only. If the recovery is equal to 70% this means that 70% of the original feed water became the purified product water and 30% remained as brine. The level of recovery possible is limited by the salinity level in the brine because at high enough concentrations salts precipitate out and interfere with whole treatment process. For this reason the user is disallowed from entering a recovery that is too high – A red warning message will pop up and the user will not be able to run the program. This recovery level will differ depending on feedwater.

4.3 Treatment Technology Selection and Optimization

The treatment selection module accomplishes two tasks: it selects optimal treatment trains for each beneficial use and it provides further information (costs, energy consumption, water quality etc) on these. The first task – treatment technology selection and optimization – uses a visual basic code that runs in the background of excel. The methodology of this selection and optimization is broadly represented in the TSM flow chart (Figure 4-11) but is described here in more detail.

When asked to select a treatment train the TSM code first determines what water quality problems exist by comparing the feed water quality to the desired water quality (the beneficial use limits or guidelines). From this it creates a list of constituents that require some removal and it calculates how much of that constituent needs to be removed in order to meet the guidelines. Next the TSM queries its database. The database includes about 40 treatment processes with removal capabilities for up to 47 different constituents (e.g., iron, total nitrogen). From this data it selects treatment processes that adequately remove each constituent or combinations of treatments which can achieve the same. It then organizes these into a master list of treatment trains by performing a permutation with built-in duplicate removal on the combined process-constituent permutations. This master list can be quite long especially if a large number of treatment processes can successfully treat the water. In that case the treatment trains have to be prioritized so that the best train can be suggested to the user. This prioritization or optimization, as it is usually called, is based on the selection criteria entered by the user. Each treatment is pre-scored based on its compatibility with the selection criteria. For example a treatment requiring little space is pre-scored as a 5 for 'small footprint' to indicate that it fits this criterion well. When the user enters a 5 to indicate that a small footprint is necessary this treatment process will get a high score (5x5 = 25) and will be prioritized over a treatment that requires a large amount of space (1x5 = 5). Once each process is scored the scores are added together and then inverted and chosen for the lowest score. This is to ensure that shorter trains are given higher priority than longer trains. Finally, once all the scores are collated the three trains with the highest scores are selected and displayed for the user.

4.4 Output

The main output of the Treatment Selection Module is the 3 treatment trains for each beneficial use. The resulting product water quality as well as costs, energy requirements etc are given for each train. The outputs and user actions required are detailed in Table 4-7.

4.5 Nexus with other Modules

4.5.1 Water Quality Module

The TSM receives water quality information from the WQM. It also receives plant capacities (average and peak flow rates).

4.5.2 Beneficial Use Screening Module

The results of the TSM, the treatment trains and their capital costs and energy consumption, are fed into the BSM. These are used directly in the BSM's Screening Matrix to provide the user with a range of complexity and costs for the treatment processes selected for each beneficial use category.

4.5.3 Beneficial Use Economic Module

The treatment trains, costs and energy consumption from the TSM are directly input to the Cost Template of the BEM. However, the BEM is not the module directly following the TSM – the user must first enter data into the BSM or Beneficial Use Screening Module before proceeding to the BEM.

Table 4-7 Description of TSM Outputs

Output	User input	Description
Treatment trains for each beneficial use	Yes	Three treatment trains are provided for each beneficial use. The user must select one treatment train that they wish to evaluate further for each beneficial use. They do this by clicking on the radio button that corresponds to that treatment train. The user can select only one train because the later modules (BSM and BEM) accept only one train per intended use. But why then provide three options? The options are provided so that the user has some choice, is able to see the different treatments capable of treating their water and can avoid certain treatments if they so choose. If the user is unsure of which train to choose they should select the first option for each beneficial use – this is the option that scored highest in terms of the selection criteria.
Energy, cost and equipment life for each train	No	The energy consumption, cost and equipment life for each treatment train can be viewed in the output of the TSM. The user needs to click on the **+** button in left hand margin. Each **+** button corresponds to one treatment train. When this is clicked more lines will become visible showing the costs and energy consumption for each process. These costs etc. are generic values which are typical of that individual treatment process. They are estimates only; they are not specific to any one manufacturer and will vary, perhaps even substantially, depending on the exact site conditions and location. In this module the capital costs are related only to plant capacity (the average and peak flow rates). The energy consumption is related to plant capacity, feed TDS and recovery.
Water quality for each treatment train	No	The water quality of the product stream as well as the brine stream can be viewed by clicking on the button entitled 'detailed water quality' beside each beneficial use. This will open a sheet showing the water qualities for that beneficial use and for the treatment train that is currently selected (via the radio buttons on the main output page). If the user is unsure of which beneficial use or treatment train they are viewing they need only look at the top of this page – the beneficial use and treatment train are listed there. In the table below these are the various constituents and their concentrations in the feed and in the product and brine streams after treatment with this particular train. The beneficial use guidelines are also shown on the right hand side and any values exceeding these are highlighted in red. In some cases the program will not find a treatment train able to remove enough of the problem constituents and in this case a warning message will appear in red at the top of the page. This does not mean that the water is untreatable. The program uses generic removal capabilities typical of each treatment process. Also, many treatment processes can be modified or optimized. Further, the program does not have an exhaustive list of treatment processes and there may be many specialized processes quite capable of treating the water that are not included in this program.

Section 5: Beneficial Use Screening Module

5.1 Introduction

5.1.1 Purpose of BSM

The purpose of the Beneficial Use Screening Module (BSM) is to help produced water generators, potential beneficial Users, and other stakeholders identify key issues regarding different potential beneficial use projects.

5.1.2 Description of BSM

Table 5-8 describes the worksheets that comprise the BSM.

Table 5-8 Overview of BSM Worksheets

Worksheet (Tab)	User Input Required	Description
BSM_Input	Yes	User enters or selects information about current disposal methods from a drop down menu. The User also selects screening criteria bins and selects the relative importance of the screening criteria.
Screening Matrix	No	Screening matrix tables present a qualitative comparison of the feasibility, complexity, and value of different beneficial use categories. Results from the TSM are provided in the matrix to compare treatment requirements for various beneficial use categories.
Bin Influences	No	Summarizes the feasibility for each screening criteria and associated bin. This information is input into the Screening Matrix tab to assess the feasibility of each beneficial use based on the User specified bins and the relative importance of each criterion.
Bin Influence Graphs	No	Provides a graphical representation of the Bin Influences tab and provides the rationalization for the relative feasibility assigned to each bin.
Potential Benefits	No	Provides qualitative and/or quantitative estimated potential economic, environmental, and social values - sometimes referred to as Triple Bottom Line (TBL) Benefits - associated with each beneficial use. An estimation of emissions for energy sources and an assessment of carbon footprint are also provided in this worksheet.

The results from the BSM are used in the Beneficial Use Economic Model (BEM).

5.1.3 Module Flowchart

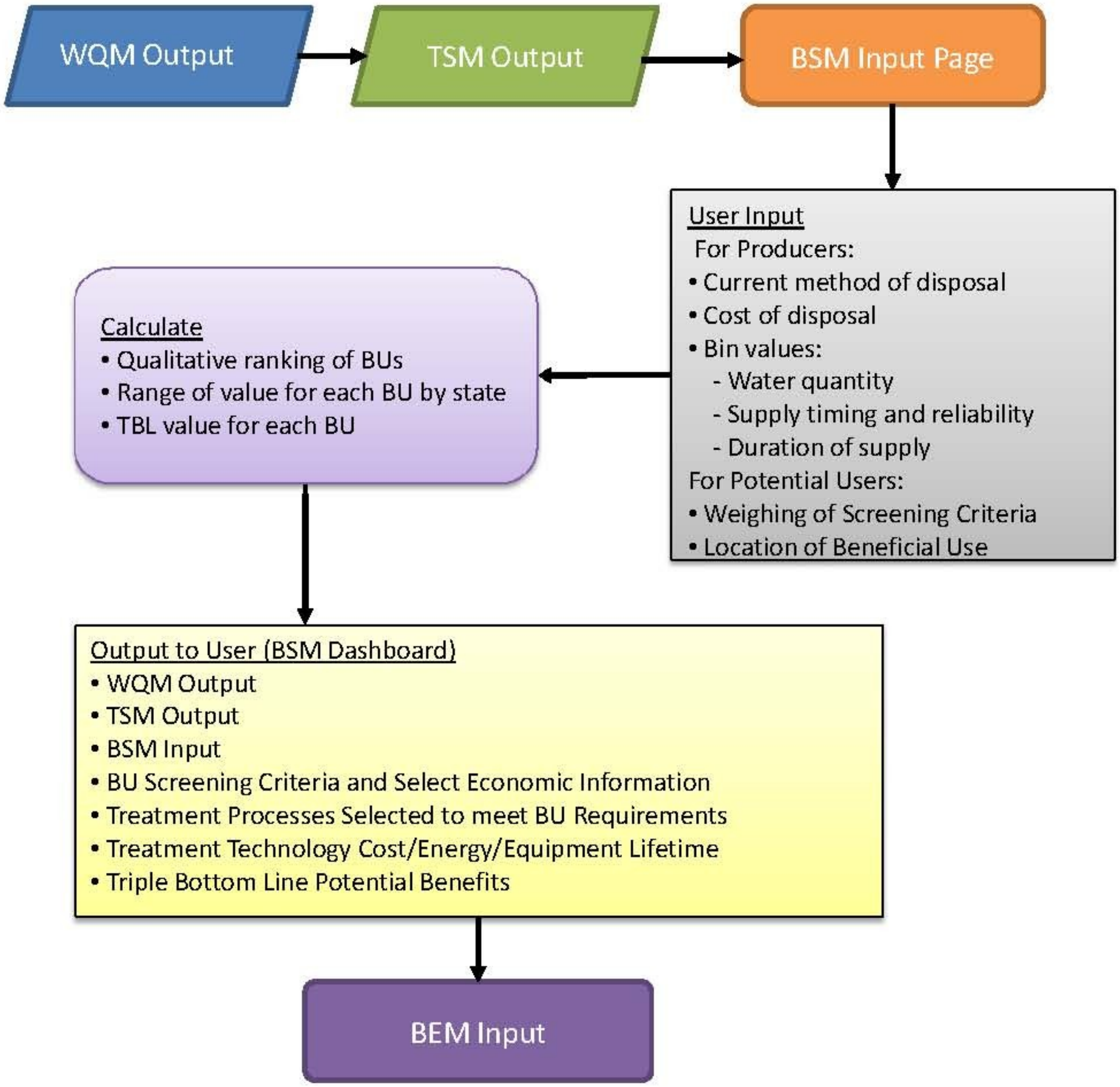


Figure 5-12 BSM Flowchart

5.2 *Input*

A description of BSM input requirements is provided in Table 5-9.

Table 5-9 Description of BSM Input

Input	Unit(s)	Description
Current cost of disposal	$/bbl, $/gal, or $/AF	User selects units from drop down menu and enters the $ per unit cost for current disposal of produced water. Conversions between units are provided in the 'Conversion' worksheet for reference.
Current Method of Disposal	N/a	User selects applicable method of disposal from drop down menu.
Select Water Quantity Range	N/a	User selects one of the following screening criteria bins from the drop down menu: Bin 1 - Base flow < 1,000 gal/day Bin 2 - 1,000 gal/day < Base flow < 10,000 gal/day Bin 3 - 10,000 gal/day < Base flow < 0.1 MGD Bin 4 - 0.1 MGD < Base flow < 1 MGD Bin 5 - 1 MGD < Base flow < 5 MGD Bin 6 - Base flow > 5 MGD
Select Supply Timing and Reliability Range	N/a	User selects one of the following screening criteria bins from the drop down menu: Bin 1 - Intermittent flow subject to stoppage Bin 2 - Intermittent flow for 5 years Bin 3 - Consistent base flow for 1 year Bin 4 - Consistent base flow for 5 years Bin 5 - Consistent base flow for 30 years
Select Duration of Supply Range	N/a	User selects one of the following screening criteria bins from the drop down menu: Bin 1 - Base flow less than 5 years Bin 2 - Base flow for at least 5 years Bin 3 - Base flow for at least 30 year
Importance of Screening Criteria	N/a	User selects the relative importance, or weighting, of each screening criteria (water quality, supply timing and reliability, and duration of supply) from drop down menu. A weighting of 5 is extremely important and a weighting of 1 is not important.

The BSM input is used to create the Screening Matrix table.

5.3 *Beneficial Use Screening Evaluation*

The BSM screening evaluation is based on a qualitative ranking of the relative feasibility of each beneficial use category based on the ranges selected by the User for each screening criteria:

- Water Quality,
- Supply Timing and Reliability, and
- Duration of Supply

The Bin Influences tables and graph worksheets summarize the associated feasibility for each screening criteria and bin. This information is input into the Screening Matrix worksheet to assess the feasibility of each beneficial use based on the User specified bins and the relative importance of each criterion.

For example, for the relative feasibility of the Surface Water Discharge/ Instream Flow Augmentation category is evaluated in the following manner for each screening criteria:

- **Water Quality** – flows less than 1 MGD (Bins 1-3) are assumed to be most feasible (5) as these small flows can be more easily absorbed by the naturally occurring flow in a stream. Whereas a larger quantity of flow, 1 to 5 MGD (Bins 4-5) would need a higher flow receiving water to provide sufficient dilution and avoid creation of a stream with produced water dominated flow.
- **Supply Timing and Reliability** – Intermittent and unreliable flows have the potential to create unfavorable environmental conditions as habitat created by the additional flows would be difficult to sustain when flows cease, therefore Bins 1-2 are least favorable for this criterion. Consistent base flows up to 5 years (Bins 3-4) would be slightly more feasible, but could similarly create unfavorable environmental conditions once produced water contributions cease. Consistent base flows for over 30 years (Bin 5) would be the most favorable for creating and sustaining habitat. Storage of produced water can increase the feasibility of supply timing and reliability by providing a means to capture peak flows and provide a more consistent base flow or a controlled seasonal 'pulse' release that is timed to support a specific environmental period (such as fish migration).
- **Duration of Supply** – Base flows less than 5 years have the potential to create unfavorable environmental conditions as habitat created by the additional flows would be difficult to sustain when flows cease, therefore Bin 1 is not very favorable for this criterion. Base flows for at least 5 years (Bin 2) is slightly more favorable in terms of providing a longer-term supply. It follows that guaranteed base flows for at least 30 years (Bin 3) would be the most favorable as created habitat could be sustained for an extended period.

The beneficial use screening evaluation is input into the Screening Matrix worksheet for the User selected bins.

5.4 Output

The table at the top of the Screening Matrix worksheet provides a color coded and quantified assessment of the feasibility and relative complexity between beneficial use categories based on the User input.

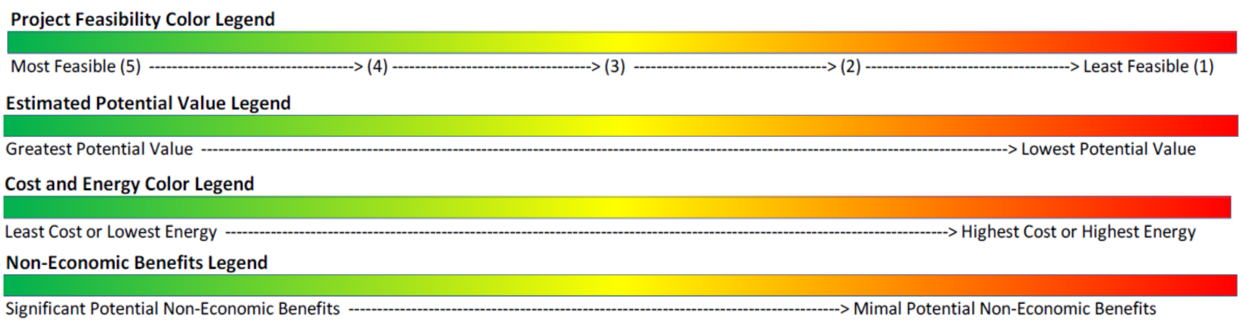
1. The feasibility score for each beneficial use, screening criteria, and associated bin is pulled from the Bin Influences worksheet.
2. The weighting of relative importance of each criterion (shown in the second column) is then applied to the relative feasibility based on bins to give a Screening Criteria Summary score.
3. The intent of these scores is to provide a means of comparing the feasibility or relative complexity between beneficial use categories.
4. A range of estimated potential values for each beneficial is also provided to give the User a sense of the potential economic value of providing produced water for a beneficial use.

Additional information is provided for each beneficial use category, including:

- The treatment processes selected to meet each beneficial use category requirements, as determined by the TSM.
- The associated costs, energy requirements, and useful life for the treatment processes

selected to meet each beneficial use category requirements, as determined by the TSM.
- Potential non-economic benefits associated with each beneficial use category requirements, based on the information provided in the Potential Benefits worksheet.

The ten beneficial uses are qualitatively ranked based on project feasibility, estimated potential value, cost and energy, and non-economic benefits. Thus the User can identify the top 2 or 3 beneficial uses that have a greater potential for feasibility or economic return to focus on for additional assessments.



The complexity and cost of the treatment process and the identification of other potential benefits can also help the User to refine the top beneficial uses that may be of interest in pursuing further.

5.5 Nexus with other Modules

5.5.1 Water Quality Module (WQM)

The WQM provides inputs for the TSM but does not directly interact with the BSM.

5.5.2 Treatment Selection Module (TSM)

Results from the TSM are directly input into the Screening Matrix worksheet to provide the user with a range of complexity and costs for the treatment processes selected for each beneficial use category.

5.5.3 Beneficial Use Economic Module (BEM)

The BSM helps the user to identify the top 2 or 3 beneficial uses to further asses in the economic evaluation. Information in the Potential Benefits worksheet is also referenced in the BEM.

Section 6: Beneficial Use Economic Module

6.1 Introduction

6.1.1 Purpose of BEM

The purpose of the Beneficial Use Economic Module (BEM) is to help produced water generators, potential beneficial users, and other stakeholders identify estimated, planning-level capital and operational and maintenance (O&M) costs for potential beneficial use projects. The cost evaluation can be performed for multiple beneficial use categories or variations on a single beneficial use category to allow for comparison of the relative costs between scenarios. Potential social, environmental and other benefits are also estimated quantitatively and/or qualitatively in the BEM to provide a non-economic assessment of beneficially using produced water.

6.1.2 Description of BEM

Table 6-10 describes the worksheets that comprise the BEM.

Table 6-10 Overview of BSM Worksheets

Worksheet (Tab)	User Input Required	Description
BEM_Input	Yes	User defines a project, selects a beneficial use, and enters or selects information for the project scenario that will be used in the economic evaluation. A more detailed discussion of each input item is provided in Table 6-11.
Cost Template	Yes	Provides an Engineer's Opinion of Probable Costs for the defined project scenario, providing a capital cost, annualized capital cost, and O&M costs. The User can choose to modify default unit costs and other values based on project-specific details. The User can memorializes the results of a project scenario by clicking the 'SAVE' button on this worksheet.
Cost Summary	No	Summarizes the range of estimated capital and annualized cost for project scenario presented in the Cost Template worksheet. Potential social, environmental and other benefits are also estimated quantitatively and/or qualitatively.
Compare Uses	No	Compares the results of the BEM for the memorialized project scenarios, allowing the User to compare multiple beneficial uses or variations on a project scenario based on the results from the four modules and user selected inputs.
Assumptions	No	Provides capital costs, unit costs, equipment life, cost assumptions, and calculation assumptions that are used in the Cost Template to determine the Engineer's Opinion of Probable Costs. Contingencies, and default values supporting the BEM are also provided.
Conversions	No	Provides conversions for flow volumes, flow rates, area, and energy emissions.
ENR	No	Provides the construction cost index for Denver, TX, and Denver, CO as reported periodically in the *Engineering News-Record (ENR)*, which measures the effects of wage rate and material price trends in the construction industry. The ENR index is used for cost and location escalation in the BEM evaluation.

6.1.3 Module Flowchart

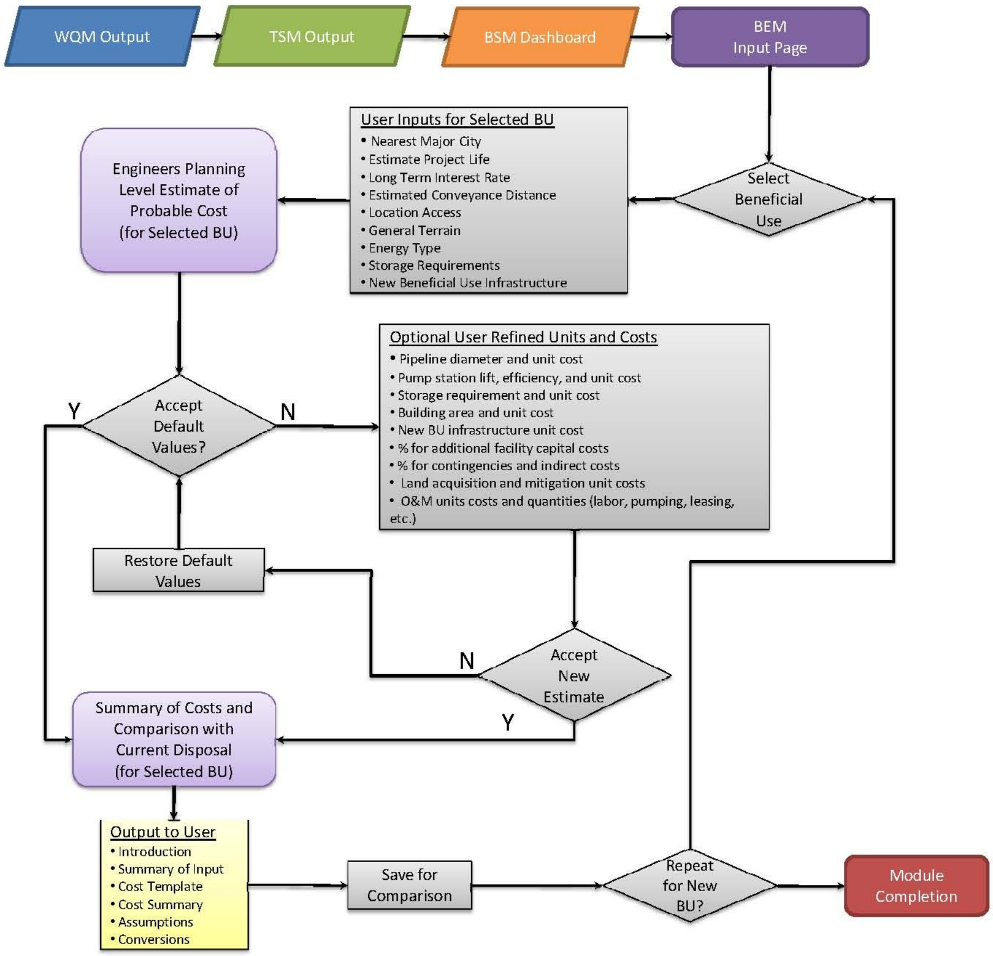


Figure 6-13 BEM Flowchart

6.2 Input

A description of BSM input requirements is provided in Table 6-11.

Table 6-11 Description of BSM Input

Input	Unit(s)	Description
User Chosen Project Name	N/a	User enters a project name to reflect the project scenario. It is recommended to use numbers or letters to distinguish variations on a similar scenario.
Select Beneficial Use for Project Cost Estimate	N/a	User selects beneficial use category from drop down menu.
Project Date	N/a	User enters the month and year anticipated for project construction. This date is used to escalate costs based on the ENR Index.
Project Location	N/a	No User input required. Transferred from WQM.
Nearest Major City	N/a	User selects nearest major city.

Input	Unit(s)	Description
ENR Index Reference City	N/a	User selects either Dallas (TX) or Denver (CO) from drop down menu. This reference city is used for cost/location escalation based on the ENR Index.
Estimated Project Life	years	User enters value (typically 1 through 50 years) representing the estimated life for the project. The years should correlate with the Duration of Supply bin selection in the BSM.
Long-Term Interest Rate	%	User selects long-term interest rate from the drop down menu. This value is used to calculate the annualized capital cost over the life of the project.
Estimated Project Area	acres	User enters the estimated project area. This value is particularly it is anticipated that the project will require purchasing or leasing land.
Ownership	N/a	User selects one of the following from the drop down menu: Currently owned, Leased from Bureau of Land Management (BLM), or Purchase Required. A default estimated $/acre annual cost for leased land and $/acre capital cost for purchased land is listed in the Assumptions worksheet.
Estimated Conveyance Distance	miles	User enters estimated miles from produced water site to selected beneficial use. This value will be used to estimate the capital cost of pipelines and head loss for conveyance.
General Type of Terrain	N/a	User selects one of the following from the drop down menu: Flat, Hilly, or Steep. The type of terrain is used to estimate the static lift for pump capacity and associated conveyance energy requirements. Refer to Assumptions worksheet for description of calculations.
Energy type	N/a	User selects one of the following from the drop down menu: Remote (diesel), Remote (natural gas), Grid transmission lines (CO, MT, NM, UT, WY). The energy type is used to estimate the emissions (CO_2, SO_2, NO_2) and subsequent potential offsets and carbon footprint.
Energy Unit Cost	$/kWh	No User input required. Transferred from TSM.
Storage Tank Volume Required	MG	A storage tank or pond would be used to equalize inflow into the treatment plant, thereby reducing its required capacity. The User can switch between units of hours and days, to calculate the estimated storage volume as: hours/24 x (peak daily flow - treatment design flow) or days x (peak daily flow - treatment design flow). The User should enter 0 in the yellow box if storage is not required. The treatment design flow is determined in the TSM.
Storage Pond Volume Required	MG	
New Beneficial Use Infrastructure #1	N/a	Potential new infrastructure that may be associated with the selected beneficial use is identified in #1 and #2; however, the User may select "Not Needed" from the dropdown menu if existing infrastructure is already in place or not required for the project. A list of potential new infrastructure and the associated unit costs is provided in the Assumptions worksheet.
New Beneficial Use Infrastructure #2	N/a	
Period of Operation of Treatment Plant	% of year	User selects 0% to 100% from the drop down menu based on the anticipated percent of time during the year that produced water will be conveyed to the treatment plant.
Estimated Number of Full-Time Treatment Staff	persons	The estimated number of full-time staff to operate treatment plant is determined in the TSM based on the number and complexity of processes in the treatment train.
Estimated Number of Full-Time Other Staff	persons	User enters estimated number of full-time staff to operate produced water portion of the project.

Input	Unit(s)	Description
Control source	N/a	User selects one of the following control systems from the drop down menu: SCADA (high-tech), Remote (low-tech), Manual control only. The control system type impacts the percentage used to estimate costs for electrical, I&C and control costs in the Cost Template.
Current Disposal Method	N/a	No User input required. Transferred from BSM.
Estimated Energy Required for Current Disposal	kWh/bbl	The User can manually enter the energy requirement per barrel for current disposal of produced water. If this quantity is known, the BEM will compare the energy requirements for the selected beneficial use and calculate the potential annual energy savings and potential value of avoided emissions.

The BEM input data is used to populate the quantity and unit cost data used in the Engineer's Opinion of Probable Costs for the defined project scenario.

6.3 Beneficial Use Economic Evaluation

Capital and O&M costs presented in the BEM were developed based on specific design criteria defined through the TSM, general project criteria based on professional experience, and unit costs for power, chemicals and labor representative of the Denver area (Jan 2010). This cost estimate is developed at a Class 5 level representing Planning to Feasibility level information with an estimated accuracy range between -30% and +50%(AACE 1997, DOE 1994, EPRI 1993).

6.3.1 Cost Template

Information in the Cost Template worksheet is populated with User Input from the four modules, typical values from project experience, engineering calculations and assumptions. Each line item in the Cost Template is calculated in one of three ways:

1. **Unit Cost Calculation** – where a quantity is multiplied times a unit cost to provide a total capital cost. (i.e. 200 linear feet (lf) of pipeline x $120/lf = $24,000)
2. **Lump Sum Calculation** – where the quantity (one) is multiplied by a lump sum cost to provide a total capital cost. (i.e. 1 lump sum (LS) treatment train process x $500,000/LS = $500,000)
3. **Percentage Calculation** – where a percent is multiplied by a value or sum of values. (i.e. Site development costs = 5% x Subtotal Facility Costs, which estimates the cost for grading, erosion control, cut/fill, etc.)

Capital costs are converted to annualized capital costs using the following equation:

$$\text{Annualized Capital Cost} = \text{Capital Cost} \times \frac{i \times ((i+1)^n)}{(1 + I)^n - 1}$$

Where: n = project life or facility life

i = interest rate

Annual O&M costs can be added to the annualized capital cost to estimate the total economic cost per year to construct and operate the project over the life of the project.

Capital costs can be escalated to a future date or an alternative location using the ENR Index. The ENR index measures only the price changes of respective construction *input factors* as represented by constant quantities of material and/or labor. It is not adjusted for productivity, efficiency, competitive conditions, or technology changes. Historical monthly indices from ENR are provided for Dallas, TX, and Denver, CO from Jan 2004 to Jan 2010. Estimated future potential monthly indices through Dec 2015 are estimated at a rate of 6.5%, based on potable supply price increases from MWD. The city and date used for escalation area shown in the upper right corner of the Cost Template, based on User input from the BEM_Input tab.

The Assumptions worksheet provides a more detailed discussion of the assumptions and calculations associated with each line item.

User options for the Cost Template:

- Values in **RED** can be modified by the user to more accurately reflect the costs and/or quantities in a particular region.
- Values in **BLACK** cannot be changed on this spreadsheet though modifications to the User input will change some of the cells.
- Restore default values by clicking on the **ORANGE** button to the right labeled "Restore Default Values".
- Save the current project scenario to the Cost Summary worksheet by clicking on the **BLUE** button to the right labeled "Memorialize This Scenario".

6.3.2 Cost Summary

The Cost Summary worksheet provides an overview of the economic costs of the project scenario as well as some of the non-economic benefits of beneficially using produced water.

- **Estimated Project Capital Cost** is based on the location and year of anticipated project construction.
- **Total Present Value for Life of Project** is calculated using the following equation:

$$\text{Total Present Value for Life of Project} = \text{Capital Cost} + \text{Annual Cost} \times \frac{(1+i)^{n-1}}{i \times (1+i)^{n}}$$

Where: n = project life
i = interest rate

- User can select the preferred units from the drop down menu ($/bbl, $/gal, or $/AF)
- **Estimated Range of Project Annualized Unit Costs** is calculated as -30% and +50% of the annualized capital and annual O&M costs calculated in the Cost Template. This provides the User with an idea of the range of costs for a simple to complex project and allows for comparison to the current cost of disposal (as entered by the User)
- **Estimated Value of Produced Water for Selected Beneficial Use** is estimated quantitatively in the BEM based on a literature review of the value of water in various uses (Stratus, 2009). These values will vary significantly by location and upon site specific conditions and are intended to provide a broad assessment of opportunities that may potentially be available to support the beneficial re-use produced water.
- **Potential Social, Environmental, and Other Benefits** are estimated quantitatively and/ or qualitatively in the BEM. These values will vary significantly by location and upon site specific conditions and are intended to provide a broad assessment of opportunities that may potentially be available to support the beneficial re-use produced water.
- **Potential Emissions Offset and Value** is estimated based on a broad assessment or

potential emissions savings and possible returns. These values will vary significantly by location, energy source, site-specific conditions, energy market, and the accuracy of the estimated energy for current disposal.

6.3.3 Compare Uses

The Compare Uses worksheet allows the User to compare multiple beneficial uses or variations on a project scenario based on user inputs and the results from the WQM and TSM. To save a project scenario to this worksheet, the User must click on the **BLUE** “Memorialize This Scenario” button in the Cost Template.

New Scenarios are added to Column D. The User can click on RED “Delete Last Scenario” button to remove the last Scenario created or the User can highlight any column and hold Ctrl and the “-“ key together to delete a Scenario that is no longer needed.

The User can create numerous project scenarios for a single beneficial use or for multiple beneficial uses that utilize the same water quality and quantity from the same project location. Thus it is advisable to choose a project name with versions to track cost estimates for each scenario. If the User chooses to change the project location or water quality and quantity, the User should return to the Water Quality Module by returning to the WQM to begin again.

No calculations are performed on this worksheet.

6.4 Output

The Cost Template, Cost Summary and Compare Uses worksheets, described in the previous section, are the output from BEM. It is recommended that the User print or create a PDF of the project scenarios they are most interested in so that they can preserve a high level cost summary or a more detailed cost estimate for future discussions.

6.5 Nexus with other Modules

6.5.1 Water Quality Module

The WQM provides inputs for the TSM but does not directly interact with the BEM.

6.5.2 Treatment Selection Module

Results from the TSM are directly input into the Cost Template worksheet to provide capital and O&M costs for the treatment processes associated with the selected beneficial use for the project scenario.

6.5.3 Beneficial Use Screening Module

The BSM helps the user to identify the top 2 or 3 beneficial uses to further asses in the economic evaluation. Information in the Potential Benefits worksheet is also referenced in the BEM.

Section 7: Potential Project Impacts and Technology Transfer

Potential Impacts

The guidance framework developed during this project can assist producers in selecting the most economically and environmentally sound treatment processes suitable to the specific chemistry of the water that is being produced. The framework also enables more accurate budgeting of produced water management costs for the producer. These advances will enable producers to utilize lower cost and better tailor water treatment processes and management alternatives potentially resulting in an increase of gas production.

Accomplishments

Work on this project began on September 12, 2008 and was completed on June 30, 2011. The following accomplishments can be reported.

The Technology Status Assessment describing the state-of-the-art of the proposed technologies has been prepared and submitted to RPSEA in October 2008. This document is available on the project website and can be accessed through: http://aqwatec.mines.edu/produced_water/treat/docs/Tech_Assessment_PW_Treatment_Tech.pdf

In support of the framework development, the first Stakeholder Advisory Committee (SAC) workshop was held on September 25-26, 2008 to initiate a dialogue with key stakeholders regarding barriers to beneficial use of produced water. The second SAC meeting took place on August 26-27, 2009 in conjunction with the first meeting of the project's Industry Advisory Council (IAC) to introduce and discuss the key elements of integrated framework approach and encourage collaborative interaction between industry and stakeholder representatives.

The team developed water quality database for individual basins. These databases were augmented by water quality information available in the public domain and information provided by industry partners of this study that are engaged in operations in these basins.

CSM built a comprehensive database of currently employed water treatment technologies for produced water as well as technologies that are either emerging in the desalination of saline water or are employed elsewhere to treat brackish water types. More than 50 individual processes were identified and are currently reviewed. In order to rank these treatment processes under the scope of this study, assessment criteria were developed.

Project researchers investigated commonly employed pre-treatment processes such as chemical flocculation followed by media filtration, cartridge filtration, microfiltration (MF), and ultrafiltration (UF), but also explored emerging technologies, such as ceramic UF membranes for representative produced water categories. For the representative produced water categories, CSM and ANL investigated the cost-effectiveness of conventional RO, NF, and electrodialysis reversal (EDR) treatment technologies. In addition, the team investigated the viability of non membrane-based approaches in desalination such as capacitive deionization (CDI) and ion exchange (IX) technologies for these water quality categories. In collaboration with Eltron R&D, the team also investigate novel NF and RO membranes such as fouling resistant membranes as well as membranes that were developed specifically to work with hot feed streams.

Viable processes as verified in the laboratory were pilot tested at representative production sites for field-scale validation. This validation occurred at three sites representing different water compositions, supported by the industry partners.



The team finalized a beneficial use matrix detailing the water quality requirements for beneficial non-potable and potable uses by considering state specific requirements. This document is limited to requirements set forth by states in the Rocky Mountain region.

The team developed a draft MS Excel based spreadsheet model into a CBM Produced Water Management Tool that integrates water quality information, selection of treatment processes, beneficial use options, and an economic assessment. The spreadsheet model was validated and is now available as a download from the project website: http://aqwatec.mines.edu/produced_water/tools/index.htm.

Case studies were selected to illustrate application of the CBM Produced Water Management Tool and represented a range of project conditions, water qualities, and beneficial uses. The case studies provided practical information on “lessons learned” and illustrated the decision process for selection of the most appropriate beneficial uses and the most cost-effective treatment and residuals management technologies. Case studies documented capital and O&M costs and, where applicable, any revenue streams derived from beneficial use. In addition, environmental and societal benefits were documented.

The team developed a project website that serves as clearinghouse for project technology transfer and dissipation of information. The project website went live in April 2010. http://aqwatec.mines.edu/produced_water/index.htm.

The Technology Transfer of this project is specified in Table 7.1.

Table 7.1. Technology Transfer of RPSEA Project 07122-12

Month	Conference attendance & presentation	IAC workshops	Development of website and tools			Tele-Conferencing	Monthly Expenses
			CSM - student support	Kennedy/ Jenks	ANL (including workshops)		
Sep-08	0.00	205.48	0.00	0.00	0.00	80.16	***285.64***
Oct-08	565.50	0.00	0.00	0.00	0.00	58.26	***623.76***
Nov-08	0.00	0.00	0.00	0.00	0.00	101.85	***101.85***
Dec-08	0.00	0.00	0.00	0.00	10000.00	0.00	***10000.00***
Jan-09	272.01	0.00	0.00	0.00	0.00	33.25	***305.25***
Feb-09	0.00	0.00	0.00	39628.02	4997.00	56.56	***44681.58***
Mar-09	0.00	0.00	0.00	61.97	4997.00	59.02	***5117.98***
Apr-09	976.60	0.00	0.00	26749.02	18062.63	0.00	***45788.25***
May-09	0.00	0.00	0.00	5710.99	17440.27	134.02	***23285.28***
Jun-09	0.00	0.00	0.00	0.00	16124.42	78.65	***16203.07***
Jul-09	0.00	0.00	0.00	6939.62	0.00	59.16	***6998.78***
Aug-09	361.95	3926.83	1015.00	11037.49	1805.64	33.60	***18180.51***
Sep-09	906.93	0.00	1015.00	33504.93	9871.17	44.89	***45342.92***
Oct-09	3206.24	0.00	1015.00	0.00	7782.42	78.52	***12082.18***
Nov-09	3961.99	0.00	1015.00	14998.45	0.00	28.99	***20004.43***
Dec-09	500.50	0.00	1015.00	25409.89	5769.62	31.91	***32726.92***
Jan-10	0.00	0.00	3235.82	5543.21	1059.36	61.10	***9899.49***
Feb-10	0.00	468.35	3235.82	0.00	2090.50	28.99	***5823.66***
Mar-10	928.00	0.00	3235.82	15787.93	0.00	0.00	***19951.75***
Apr-10	0.00	0.00	3235.82	12265.29	0.00	43.92	***15545.03***
May-10	0.00	0.00	3235.82	7679.01	0.00	28.99	***10943.81***
Jun-10	202.28	0.00	0.00	10613.02	0.00	0.00	***10815.29***
Jul-10	0.00	0.00	0.00	11688.26	0.00	0.00	***11688.26***
Aug-10	0.00	0.00	5999.32	0.00	0.00	0.00	***5999.32***
Sep-10	2407.88	0.00	5999.32	2583.18	0.00	0.00	***10990.38***
Oct-10	2683.82	0.00	5999.32	0.00	0.00	0.00	***8683.14***
Nov-10	0.00	0.00	5999.32	6273.77	0.00	0.00	***12273.09***
Dec-10	0.00	0.00	5999.32	0.00	0.00	0.00	***5999.32***
Jan-11	73.95	0.00	0.00	0.00	0.00	0.00	***73.95***
Feb-11	0.00	0.00	0.00	19610.74	0.00	0.00	***19610.74***
Mar-11	0.00	0.00	0.00	45332.42	0.00	0.00	***45332.42***
Total	***17047.65***	***4600.66***	***51250.7***	***301417.2***	***100000.03***	***1041.825***	**$475,358.07**

Technology Transfer in form of presentations and publications are summarized below. Additional publications are still under preparation for submission to peer-reviewed journals:

Publications

1. Drewes, J.E., Hancock, N., Benko, K., Dahm, K., Xu, P., Heil, D. and Cath, T. (2009). Treatment of Coalbed Methane (CBM) Produced Water. Exploration and Production: Oil and Gas Review. 7(2): 126-127.
2. Dahm, K., Guerra, K., Xu, P., Drewes, J.E. (2011). A Composite Geochemical Database for Coalbed Methane Produced Water Quality in the Rocky Mountain Region. Environmental Science and Technology, 45(18), 7655–7663.

Presentations

1. Tzahi Y. Cath, Oil and Gas Produced Water Treatment, Opportunities, and Environmental Implications. A lecture to the Water Reuse (CVEN 5834) course at the CU Boulder Environmental Engineering Department, February 21st, 2011.
2. Tzahi Y. Cath, Coal Bed Methane (CBM) Development and Environmental Impacts of CBM Produce Water. A lecture at the Environmental Impacts of Natural Resource Development course at the CSM Petroleum Engineering Department, February 3rd, 2011.
3. Tzahi Cath, Jörg E. Drewes, Pei Xu, Coalbed methane produced water: quantity, quality, and potential reuse in the Rocky Mountain basins, 2011 Piceance Basin, Mamm Creek Field RPSEA Project Review, April 21, 2011.
4. Pei Xu, Tzahi Cath and Jörg Drewes. (2011). Novel and Emerging Technologies for Produced Water Treatment. US EPA Technical Workshops for the Hydraulic Fracturing Study. Water Resources Management, March 29-30, 2011.
5. Jörg E. Drewes, Tzahi Cath, Pei Xu, Nathan Hancock, Katharine Dahm, Katherine L. Guerra and Dean Heil (2010). An Integrated Framework for Treatment and Management of CBM Produced Water. 25th Annual WateReuse Symposium, Washington D.C., September 13, 2010
6. Pei Xu, Xanthe Mayer, Katharine Dahm et al. (2010). Feasibility and Economic Analysis of Beneficial Use of Produced Water. 17th International Petroleum and Biofuels Environmental Conference, San Antonio, Texas, August 30-September 2, 2010.
7. Jörg E. Drewes, Tzahi Cath, Pei Xu, Nathan Hancock, Katharine Dahm, Katherine L. Guerra and Dean Heil (2010). An Integrated Framework for Treatment and Management of CBM Produced Water. 17th International Petroleum and Biofuels Environmental Conference, San Antonio, Texas, August 30-September 2, 2010.
8. Katharine G. Dahm, Katherine L. Guerra, Pei Xu, Nathan Hancock, Tzahi Cath, Jorg E. Drewes. Coalbed Methane Produced Water Usability through Characterization. 17th International Petroleum and Biofuels Environmental Conference, San Antonio, Texas, August 30-September 2, 2010.
9. Xanthe Mayer, Katharine Dahm, Tzahi Y. Cath, Nathan T. Hancock, Pei Xu, Katherine L. Guerra, Jörg E. Drewes From Waste to Resource – an Excel® Application to analyze water quality and select treatment for CBM produced water. 17th International Petroleum and Biofuels Environmental Conference, San Antonio, Texas, August 30-September 2, 2010.
10. Nathan T. Hancock, Xanthe Mayer, Nathan Walker, Katharine Dahm, Dean Heil, Pei Xu, Jörg E. Drewes, Tzahi Y. Cath. Novel thermally/chemically resistant NF membranes for sustainable reclamation of CBM co-produced water. 17th International Petroleum and Biofuels Environmental Conference, San Antonio, Texas, August 30-September 2, 2010.
11. Stewart, D.R., Cath, T.Y., Veil, J., Xu, P., Schreck, S., Panel discussion: Challenges and opportunities of treatment, beneficial use, and management of CBM produced water, the 17th International Petroleum & Biofuels Environmental Conference (IPEC), September 1, 2010, San Antonio, Texas.
12. Mayer, X.M., and Cath, T.Y., From waste to resource: the treatment selection module: An Excel application to select optimal water treatment trains for reuse of coal-bed methane produced water, the 7th Annual RMAWWA/RMWEA Student Conference, May 18, 2010, Boulder, Colorado.

13. Pei Xu, Xanthe Mayer, Katharine Dahm et al. (2010). Evaluation of Beneficial Use Options of Produced Water. 2010 National Groundwater Association Ground Water Summit, April 12, 2010, Denver, CO.

14. Jörg E. Drewes, Tzahi Cath, Pei Xu, Nathan Hancock, Katharine Dahm, Katherine L. Guerra and Dean Heil (2010). An Integrated Framework for Treatment and Management of CBM Produced Water. 2010 National Groundwater Association Ground Water Summit, April 12, 2010, Denver, CO.

15. Nathan Hancock, Xanthe Mayer, Katie Benko, Tzahi Cath, Jörg Drewes, Pei Xu, and Katharine Dahm (2010). CBM Produced Water Treatment Selection Module – A Tool to Provide Treatment Alternatives to Improve Water Quality. National Groundwater Association Ground Water Summit, April 12, 2010, Denver, CO.

16. Katharine Dahm, Katie Guerra, Nathan Hancock, Xanthe Mayer, Pei Xu, Dean Heil, Tzahi Cath, and Jörg Drewes. (2010). Understanding Coalbed Methane Produced Water Quality Variability to Design Treatment Processes for Beneficial Use. 2010 National Groundwater Association Ground Water Summit, April 12, 2010, Denver, CO.

17. Xu, P., Benko, K., Hancock, N., Cath, T. and Drewes, J.E. (2009). Beneficial Use Options and Limitations of CBM Produced Water. 16th International Petroleum and Biofuels Environmental Conference, Houston, Texas, November 11-13, 2009.

18. Cath, T, Hancock, N., Xu, P., Benko, K. and Drewes, J.E. (2009). Emerging Treatment Processes for CBM Produced Water Purification. 16th International Petroleum and Biofuels Environmental Conference, Houston, Texas, November 11-13, 2009.

19. Drewes, J.E., Cath, T, Xu, P., Hancock, N., Dahm, K., Benko, K. and Heil, D. (2009). Opportunities, Challenges, and Research Needs for Beneficial Use of CBM Produced Water. 16th International Petroleum and Biofuels Environmental Conference, Houston, Texas, November 11-13, 2009.

20. John Veil. (2009). Regulations and Impediments for Treatment and Beneficial Use of CBM Produced Water. 16th International Petroleum and Biofuels Environmental Conference, Houston, Texas, November 11-13, 2009.

21. Katharine Dahm. (2009). Predicting Water Quality Variability to Design Treatment Processes for Beneficial Use. 16th International Petroleum and Biofuels Environmental Conference, Houston, Texas, November 11-13, 2009.

22. Nathan Hancock. (2009). Selection and Design of Integrated Treatment Processes for CBM Produced Water Purification. 16th International Petroleum and Biofuels Environmental Conference, Houston, Texas, November 11-13, 2009.

23. Jean Debroux. (2009). The Beneficial Use Screening Module and the Beneficial Use Economic Module. 16th International Petroleum and Biofuels Environmental Conference, Houston, Texas, November 11-13, 2009.

24. Tzahi Cath. (2009). CBM Produced Water Treatment and Beneficial Use Information Center: A New Website. 16th International Petroleum and Biofuels Environmental Conference, Houston, Texas, November 11-13, 2009.

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Glossary

Alkalinity: A measure of the ability of a solution to neutralize acids to the equivalence point of carbonate or bicarbonate.

Aquifer: A body of rock that is sufficiently permeable to conduct groundwater and to yield economically significant quantities of water to wells and springs.

Aquifer storage and recovery (ASR) – ASR is a process in which clean water is injected into a shallow aquifer, stored for some period of time, and then withdrawn for later use.

Barrel (bbl) – In U.S. oil and gas operations, volumes of oil and water are traditionally expressed using the unit of barrels. 1 bbl = 42 U.S. gallons.

Basin: A closed geologic structure in which the beds dip toward the center; the youngest rocks are at the center of a basin and are partly or completely ringed by progressively older rocks.

bcf – billion cubic feet, a unit of measure for natural gas production

Beneficial use – This term is used here to describe a secondary use or reuse of produced water for a purpose that has a positive value to some entity or to the environment. This document describes a variety of potential beneficial uses for produced water.

Biogenic: Produced by living organisms or biological processes.

Bin – Bin is used to describe a unit of subdivision within a ranking scale. For example, bins established for different concentration ranges of total dissolved solids are used as part of the decision process in this document.

Biocide – Biocides are chemicals added to a process to control microbial growth. Biocides are often injected into oil and gas wells to prevent growth of organisms that could cause corrosion within the well. Biocides may end up in produced water.

Bituminous: The most abundant rank of coal. It is dark brown to black and burns with a smoky flame.

Brackish Water: Water that contains relatively moderate concentrations of any soluble mineral salts. Brackish water is saltier than fresh water but not as salty as salt water or brine water.

Brine: Water containing relatively large concentrations of dissolved mineral salts, particularly sodium chloride. Brine can have higher salt concentrations than ordinary ocean water. Occasionally, this term is used to describe the residual, untreated waste from treatment processes.

Casing – Casing is the pipe used to line oil and gas wells. Most wells are constructed using several concentric sets of casing. Once a section of well is drilled, casing is inserted into the well, and it is cemented into place.

Cement – Following placement of casing in a well, cement is pumped into the annular space between the casing and the rock wall of the well. Cement is used to create and impermeable seal in the annular space that blocks vertical migration of fluids.

Chemical additives – During well drilling and production, various types of chemicals may be injected into a well to control undesirable chemical or biological processes. Examples of chemical additives are biocides, corrosion inhibitors, scale inhibitors.

Coal bed methane (CBM) – Methane is generated during coal formation and is contained in the coal microstructure. Typical recovery entails pumping water out of the coal to allow the gas to escape. Methane is the principal component of natural gas.

Coalification: Compression and hardening over long periods of time, the processes by which coal is formed from plant materials.

Completion: The activities and methods to prepare a well for production. Includes installation of equipment for production from a gas well.

Concentrate – Concentrate refers to one of two byproducts resulting from treatment of salty water or produced water. One of the byproducts is clean water, while the other byproduct contains all the salt and other contaminants removed by the treatment process. The levels of these parameters are higher in the concentrate than they were in the untreated water.

Condensate – Condensate is a natural gas liquid recovered from gas wells from lease separators or field facilities. It is light in density and is similar to gasoline.

Development Well: A well drilled in proven territory (usually within 1 mile of an existing production well).

Desalination: Referring to processes that remove excess salt and other minerals from water.

Desorb: To remove an absorbed or adsorbed substance.

Disposal Well: A well into which produced water from other wells is injected into an underground formation for disposal.

Dry Hole: Any well incapable of producing oil or gas in commercial quantities. A dry hole may produce water, gas or even oil, but not enough to justify production.

Electrical conductivity – Conductivity is easily measured with a meter. It can be correlated to the total dissolved solids or salinity of a water sample.

Enhanced Recovery: The use of artificial means to increase the amount of hydrocarbons that can be recovered from a reservoir. A reservoir depleted by normal extraction practices usually can be restored to production by secondary or tertiary methods of enhanced recovery.

Ephemeral Stream: streams that flow only during and immediately after precipitation.

Exploration: The process of identifying a potential subsurface geologic target and the active drilling of a borehole designed to assess the coal bed methane potential.

Exploration Well. A well drilled in an area where there is no oil or gas production.

Formation: A rock body distinguishable from other rock bodies and useful for mapping or description.

Frac flowback water – Frac flowback water is water that has been injected into a formation under high pressure for hydraulic fracturing, and then returns to the surface. Much of the flowback returns to the surface within the first few days or weeks following the hydraulic fracturing job. Smaller volumes of flowback may return to the surface over many months.

Gas Shale: Natural gas produced from shale. Shale is a fine-grained sedimentary rock whose original constituents were clay minerals and mud.

Groundwater: Subsurface water that is in the zone of saturation.

Higgins Loop: A method of ion exchange where the ion exchange resin is continually regenerated through a cycling process.

Hydraulic fracturing (frac job) – Hydraulic fracturing is a process used to prepare or stimulate a formation to produce more hydrocarbons. A combination of fluid and proppant (usually sand) is injected through a well into a producing formation. The pressure is raised to a level high enough that the formation near the well develops cracks or fractures. The frac fluid and proppant enter the fractures. When the pressure is dropped later, most of the liquid (frac flowback water) returns to the surface. However, the proppant remains in the fractures and holds them open, thereby allowing the oil or gas to flow more freely to the production well.

Hydrostatic pressure – Hydrostatic pressure is the fluid pressure in a formation caused by the weight of overlying fluids.

Impoundment – An impoundment is a pond in which CBM produced water is stored or allowed to infiltrate to the subsurface. There are several terms for these impoundments: "holding ponds", "zero discharge ponds" or "infiltration ponds". Although they do not directly discharge water on the land surface, most impoundments are not lined and do discharge to the subsurface. Some percentage of seepage flow from impoundments is likely to reach stream channels via subsurface flow.

Infiltration: The flow of a fluid into a solid substance through pores or small openings; specifically, the movement of water into soil or porous rock.

Injection well – The U.S. EPA defines injection well as any bored, drilled or a driven shaft or a dug hole, where the depth is greater than the largest surface dimension that is used to inject fluids underground. Class II injection wells are used to inject produced water into the ground, inject other fluids underground to increase the recovery of hydrocarbons, or to store hydrocarbons underground.

Intermittent Stream: A stream that flows most of the time but occasionally is dry or reduced to pool stage when losses from evaporation or seepage exceed the available stream flow.

Ion Exchange: A water treatment technique that employs various adsorptive polymeric resins to remove dissolved mineral salts from a solution.

Lignite: A brownish-black coal that is intermediate between peat and subbituminous coal.

Mcf – thousand cubic feet, a unit of measure for natural gas production.

Monitoring: Specific studies that evaluate the effectiveness of actions taken toward achieving management objectives.

Mmcf – million cubic feet, a unit of measure for natural gas production.

Natural gas - gaseous mixture of hydrocarbon compounds, the primary one being methane.

NORM (naturally occurring radioactive material) – Some hydrocarbon bearing formations contain naturally occurring radionuclides. Crude oil, natural gas, or produced water may contain small quantities of NORM as a result of being in contact with the formation rock for many years. Typically, the concentrations of NORM in oil, gas, or water are not high enough to cause concern. However, NORM can accumulate in pipe scale or tank sludges.

NPDES – This term refers to the National Pollutant Discharge Elimination System regulatory program. NPDES permits are issued by states or EPA to regulate discharges of wastewater to surface water bodies.

Oil – Oil refers to mixture of hydrocarbons usually existing in the liquid state in natural underground pools or reservoirs. Gas is often found in association with oil.

Oil and grease – Oil and grease refers to a mixture of organic compounds that are measured using a common analytical test. There is no individual chemical called "oil and grease". Oil and grease is frequently limited in NPDES permits for discharges of produced water.

Parts per Million: A measurement to identify the amount of particulates in air or water.

Perennial Stream: A permanent stream that flows 9 months or more out of the year.

Permeability: The ease with which gases, liquids or plant roots pass through a layer of soil. Accepted as a measure of this property is the rate at which soil transmits water while saturated, and may imply how well water passes through the least permeable soil layer.

Perforating: Penetrating the well casing to open the reservoir to the surface.

pH. A measure of acidity or alkalinity. A solution with a pH of 7 is neutral, pH greater than 7 (to 14) is alkaline, and a pH less than 7 (to 0) is acidic.

Primacy – Under some federal regulatory programs, like NPDES and UIC, states can petition EPA to gain the authority to administer the program at the state level. When a state receives authority to administer the program, the state has primacy for the program.

Produced water - Produced water is water trapped in underground formations that is brought to the surface during oil and gas exploration and production.

POD: Describes the general location of a series of wells that tap individual coal seams within a single spacing unit.

Porosity: The ratio of the volume of all the pores in a material to the volume of the whole.

Produced Water: Water that exists naturally in subsurface formations along with oil and gas and is brought to the surface during the extraction process.

Residual – Residual refers to a solid or semi-solid byproduct resulting from wastewater or produced water treatment.

Reverse Osmosis: A pressure driven membrane process that is capable of transforming saline or brackish water streams into a high quality permeate stream and a low quality brine stream.

Reuse – Reuse in the context of this document refers to collecting water from natural gas production, treating it if necessary, and putting the water to another use.

Salinity – Salinity is a measure of salt content in a water sample. Salinity can also be expressed as total dissolved solids or electrical conductivity. High salinity waters cannot be put to beneficial reuse with first treating the water to remove some of the salt.

Saltwater – Saltwater is another term used interchangeably for produced water or brine.

Salinity: A measure of the mineral salts dissolved in water, usually expressed as total dissolved solids or electrical conductivity.

Shut In: To close the valves on a well so it ceases production.

Sodicity – Sodicity is a measure of the sodium concentration in a water sample.

Sodium adsorption ratio (SAR) – SAR measures the relationship between sodium concentration vs. calcium and magnesium concentration. In equation form,
SAR = $Na^{+1} / [(Ca^{+2} + Mg^{+2})/2]^{0.5}$.

Subbituminous: A black coal, intermediate in rank between lignite and bituminous coal. Distinguished from lignite by higher carbon and lower moisture content.

Tcf - trillion cubic feet, a unit of measure for natural gas production.

Total dissolved solids (TDS) – TDS is an analytical test that can be easily correlated to salinity. Because the measurement can be made easily, it is often used as a regulatory limit.

Tubing – Tubing is the innermost layer of piping in an oil or gas well (see casing). Typically, production of oil and gas occurs through the tubing.

Turbidity: An interference to the passage of light through water due to insoluble particles of soil, organic material, micro-organisms, and other materials, commonly used as an indicator of general water quality.

UIC – This term refers to the Underground Injection Control regulatory program. UIC permits are issued by states or EPA to regulate injection of fluids to underground formations.

Water rights – Water rights represent legal authorizations to withdraw and/or use natural water resources from both surface water and ground water. Water rights are administered throug state laws. Several different systems for assigning water rights can be found throughout the United States. Each state has its own unique way of allocating and sharing water.

Water Quality: The chemical, physical, and biological characteristics of water with respect to its suitability for a particular use.

Well Life: The time from which the well is drilled until the final abandonment of the well is approved.

Acronyms

ANL	Argonne National Laboratory
AQWATEC	Advanced Water Technology Center at CSM
AwwaRF	Awwa Research Foundation
BCA	Benefit-Cost Analysis
BLM	Bureau of Land Management
BOR	U.S. Bureau of Reclamation
CBM	Coal Bed Methane
CBNG	Coal Bed Natural Gas
CERI	Colorado Energy Research Institute
CSM	Colorado School of Mines
DOC	Dissolved Organic Carbon
DOE	Department of Energy
IAC	Industry Advisory Council
IRP	Integrated Resource Planning
IRWMP	Integrated Regional Water Management Plan
IOGCC	Interstate Oil and Gas Compact Commission
IX	Ion Exchange
K/J	Kennedy/Jenks Consultants
MCDA	Multi-Criteria Decision Analysis
NETL	National Energy Technology Laboratory
NF	Nano-filtration
O&M	Operation and Maintenance
PPM	Parts per Million
PW	Produced Water
PWS	Public Water Supply
R&D	Research and Development
RO	Reverse Osmosis
RPSEA	Research Partnership to Secure Energy for America
SAC	Stakeholder Advisory Committee
SAR	Sodium Adsorption Ratio
TBL	Triple Bottom Line
TCF	Trillion Cubic Feet
TDS	Total Dissolved Solids
TMDL	Total Maximum Daily Load
TOC	Total Organic Carbon
TPH	Total Petroleum Hydrocarbons
USEPA	United States Environmental Protection Agency
USGS	United States Geological Survey
WRA	WateReuse Association

Conversions

LENGTH	
1 inch	= 25.4 millimeters
1 foot	= 12 inches = 0.3048 meters
1 yard	= 3 feet = 0.9144 meters
1 mile	= 1,760 yard = 1.609344 kilometers
AREA	
1 square inch	= 6.4516 cm^2
1 square foot	= 929.0304 cm^2
1 acre	= 4,046.8654 m^2 = 43,560 ft^2
1 hectare (ha)	= 2.4710538 acres
1 square mile	= 2.5899881 km^2
VOLUME	
1 bbl (petroleum U.S.)	= 42 gallons (U.S.) = 1.289×10^{-4} acre foot = 0.158987 m^3
1 cubic yard	= 0.76455486 m^3 = 27 ft^3 = 201.974 gallons (U.S.)
1 acre foot	= 1,233.4818 m^3 = 43,560 ft^3 = 325,851.376 gallons (U.S.)
1 gallon (U.S.)	= 3.785412 L
VOLUMETIC RATE	
1 million gallons per day (MGD)	= 2,380.9524 bbl/day
1 bbl/day	= 4.2×10^{-5} MGD = 1.289×10^{-4} acre-foot/day