Chemical Engineering 4M03:
Industrial Separations Processes
Introduction to the WAVE Design Software

Custom Courseware

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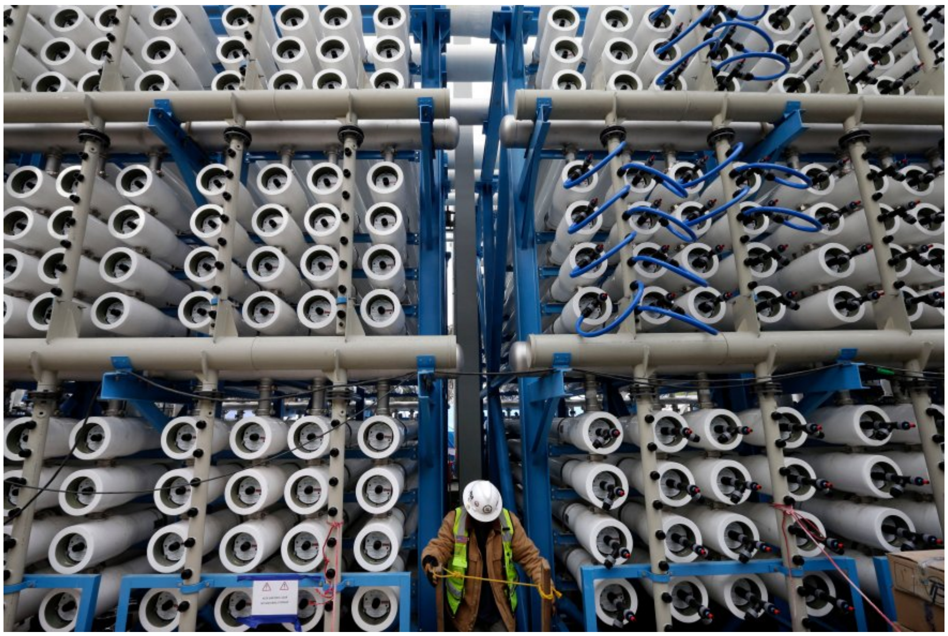
Contents

Introduction to Wave



As of 2017, the desalination plant in Carlsbad, California was the largest such plant in the Western Hemisphere, helping to provide the drought-stricken region with fresh water. In this photograph, the worker stands in front of 2,000 pressure vessels—a small subset of the entire plant. Designing and accurately simulating large membrane operations such as a desalination plant is infeasible to do by hand. Courtesy of: https://www.dailynews.com/2015/11/01/questions-and-answers-about-huge-us-desalination-plant/.

This courseware contains a set of short tutorials designed as a brief introduction to the Wave design software. The tutorials emphasize the use of Wave when modelling commercial-scale water treatment operations, with a strong focus on membrane processes. Wave is actually used by engineers, process designers, consultants, and even operators of treatment systems. Software like Wave enables engineers to better design, simulate, and/or optimize membrane processes, where doing so by-hand would likely be infeasible, such as in systems like the one in the photograph above!

DuPont has produced an excellent webinar video tutorial on how to use the Wave software. They have made it freely-available online specifically for you to use as an additional resource. You are encouraged to take advantage of this video. You can access the webinar entitled "*Introduction to WAVE: DuPont Water Solutions' multi-tech design software* at the following URL: https://gateway.on24.com/wcc/gateway/dowwaterandprocessso/906323?showId=906323&sho%20wCode=dowwaterandprocessso&partnerref=LP. Many thanks to *Caleb Funk* for making this possible.

Tutorial #1:
Getting Started with WAVE

Tutorial #1 will introduce the following information:

- What is WAVE and what is it used for?
- Downloading and installing the software
- Key features of the WAVE interface
- A practical design application for the software
- Assigning project units, water quality parameters, and flow rates

The “Water Application Value Engine” (WAVE) produced by DuPont (part of the Dow corporation) is a powerful software tool that enables the design and modelling of water treatment processes using three ubiquitous unit operations: ultrafiltration (UF), reverse osmosis (RO), and ion exchange (IX). WAVE supersedes previous DuPont software packages such as *ROSA* (for reverse osmosis) and *CADIX* (for ion exchange processes) to allow the integration of all three unit operations into a single model. According to the manufacturer, using WAVE offers engineers several important features:

- The ability to combine (in any order) UF, RO, and IX process combinations. *Think:* the sequencing of unit operations.
- The option to specify incoming feed rates or desired net-product flow rates.
- A powerful solver able to accurately predict the performance of complex designs.
- Good predictive abilities with respect to varying water chemistries and species equilibria.
- Results that reflect “realistic” changes in chemical properties (*e.g.* volumetric flow rates) due to temperature, water composition, and compressibility.
- Embedded parameters reflective of the actual performance of real Dow membrane and IX technologies.
- “Default” parameters recommended by the manufacturer so that a design can be created quickly, or in the absence of applicable information.
- The ability to introduce and override parameters to improve the accuracy of calculations.

WAVE allows engineers and process designers to predict the performance of UF, RO, and IX processes—or any combination thereof—where the feed water contains specified *aqueous salts* and/or *organic content*. The software incorporates theoretical models (*e.g.* Darcy’s Law) in addition to operating data collected and analyzed by the manufacturer. As a result, WAVE can be used to predict the behavior of systems under a variety of different conditions such a solution chemistries, temperatures, pressures, and unit operation choice/sequencing. The software will compute process parameters such as:

- System performance, including stream compositions and flow rates for every major "stream" in the design. This includes the effectiveness of the separation;
- Operating requirements, including intervals between cleaning or regeneration; and
- Estimated operating costs required in order to meet separation objectives (*e.g.* feed flow rate, product composition).

For more information, check out the DuPont website, here: https://www.dupont.com/water/resources/design-software.html.

> Much like design/simulation software that you have seen before (*e.g.* PIPE-FLO or ASPEN), WAVE offers the user a multitude of features "under the hood" to manipulate or optimize. In this collection of short tutorials, we will merely introduce you to the software and a few of its features. Be aware that WAVE is a very powerful tool for the design and simulation of UF/RO membrane and IX systems. However, it is somewhat limited in that *it was designed by the Dow corporation to market its membrane and IX products.* As such, it only contains and supports DOW offerings and not membranes/IX resins manufactured by other companies.

1.1 Downloading & Installing the WAVE Software

WAVE is *free to use* and can be downloaded from the DuPont website using this URL: https://www.dupont.com/water/resources/design-software.html. Navigate towards the bottom of the page and click on the `Download WAVE Software` button. On the next webpage entitled *Installation file for WAVE desktop for the first time*, DuPont will ask you to create an account in order to download the software. After you have created an account, return to the previous webpage. You are now able to select the "Download WAVE" hyperlink in the third list item. This will commence downloading the software. Note the process in Figure 1.1. After the .zip file downloads, extract the contents and run the installation file `WAVE_Setup_vx.xx` > `setup.exe`. Follow the instructions provided by the software.

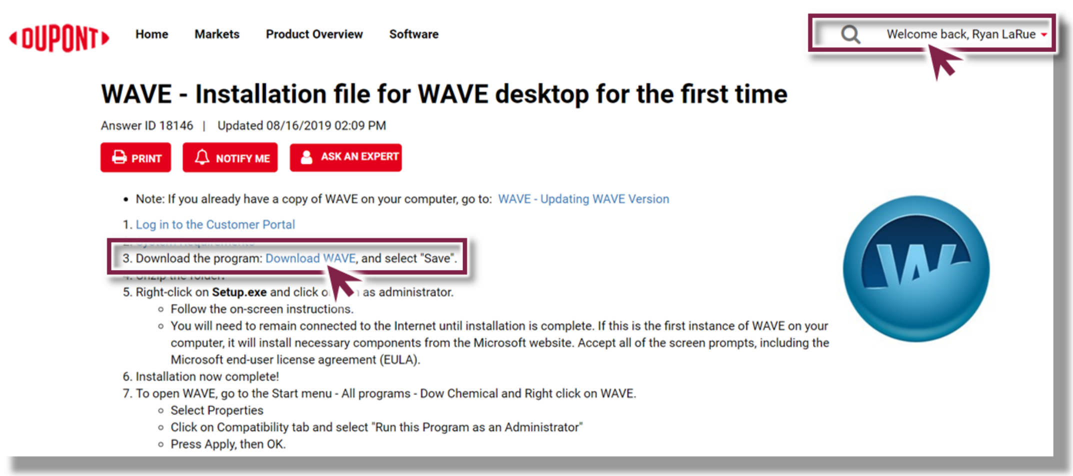


Figure 1.1: *The WAVE software can be downloaded from the DuPont website. An account must be created (see the top right of the screen) prior to downloading the installation files.*

WAVE is only supported on 32- or 64-bit Windows computers. If you use a Mac, the software will not be compatible with your computer (unless you run a dedicated Windows partition). You are welcome to work with a friend (with a Windows computer) in order to complete these short tutorials.

Before you leave the *WAVE—Installation file for WAVE desktop for the first time* webpage, scroll down towards the bottom. The user manual for the software can be downloaded—for your reference—from the WAVE User Manual hyperlink.

1.2 The Software Interface

Begin by launching the WAVE software. You should see something similar to what is shown in Figure 1.2. In order to build and run a WAVE simulation, there are four main sections of features of which you should be aware:

1. **The menu bar tabs.** At the top of the screen, you can adjust a variety of simulation settings and preferences.

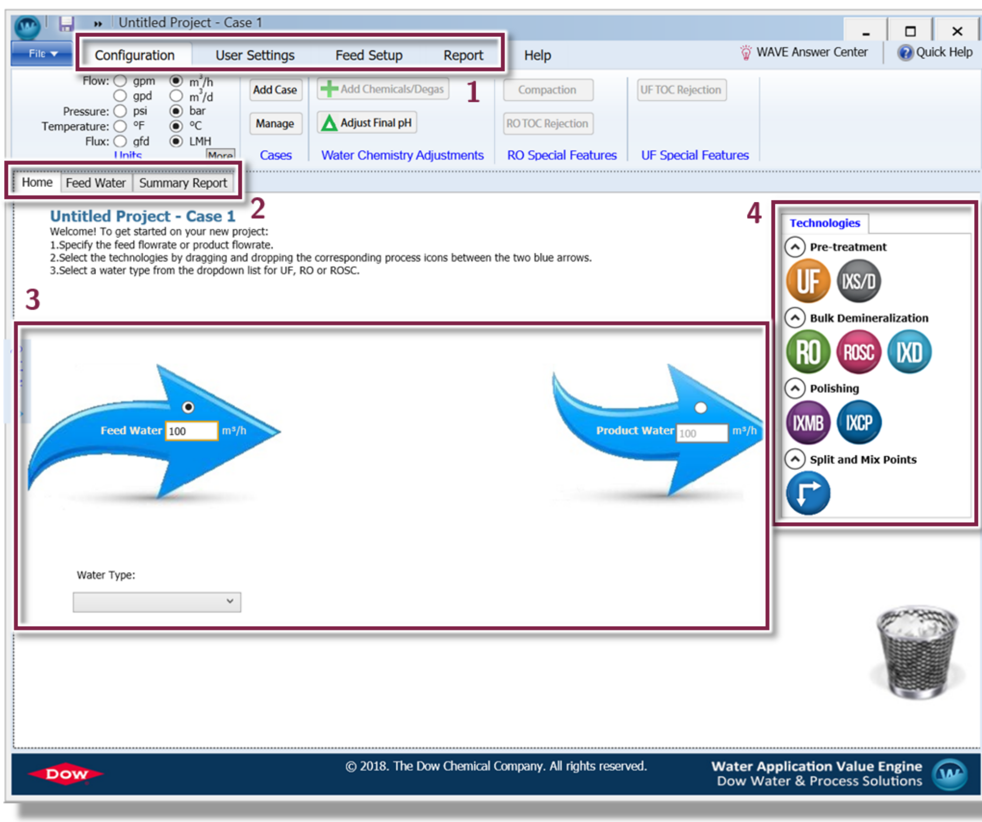


Figure 1.2: WAVE*'s home screen. The interface is perhaps less complicated-looking than other software you may have encountered. But do not be fooled:* WAVE *contains a multitude of features and parameters which can be manipulated—far more than what will be covered in this short introduction.*

2. **The project settings tabs.** Under the menu bar, these tabs allow you to adjust settings with regards to your current project and view the results of the simulation.

3. **The project flowsheet.** When the *Home* tab is selected, the project flowsheet will be displayed. Unlike programs such as ASPEN or PIPE-FLO, the flowsheet in WAVE is a *block-flow diagram.* It merely exists to indicate what treatment technologies will be used, and in what order they will be used. The exact operating specifications of these "blocks" can be adjusted in due time.

4. **The treatment technologies.** The processes which can be modelled by WAVE are located at the right side of the *project flowsheet*. These technologies can be added by dragging-and-dropping them between the *Feed Water* and *Product Water* arrows. They can be reordered in the same manner or deleted in a similar manner. Seven technologies grouped into three categories are available:

   - **Pre-treatment:** ultrafiltration (UF) and ion exchange for softening/dealkalization (IXS/D).
   - **Bulk Demineralization:** reverse osmosis (RO), reverse osmosis for small commercial systems (ROSC), and ion exchange for demineralization (IXD).
   - **Polishing:** ion exchange mixed bed (IXMB) and ion exchange condensate polishing (IXCP).

   In this courseware, we will focus on ultrafiltration and reverse osmosis membrane products, but be aware that WAVE also supports these other technologies!

We will address some of the features of WAVE in greater detail in subsequent sections of this courseware, where we will learn to use WAVE to model UF and RO systems. But first, let us consider a real-life application where WAVE could be applied.

1.3 Treating Brackish Mine Wastewater—An Application of WAVE

The following is a short case study involving an iron ore mine. The process which extracts iron metal from the surrounding ore produces a brackish (salty) water stream. While current regulations do not directly dictate the effluent water quality, it is still inadvisable for the wastewater to be directly discharged from an environmental standpoint. Furthermore, it is expected that regulations will be enacted governing the maximum ion concentrations for the discharged water. Currently, the mining operation must deal with an average of 350 m^3/h of brackish wastewater drawn from a tailings pond which has an average composition summarized in Table 1.1 below.

As the mining company suspects that new, more stringent wastewater discharge regulations are forthcoming, they wish to study the available technologies to remove the salt from the wastewater prior to discharge. In particular, the company is interested in membrane processes (*e.g.* UF, RO) and seeks to answer the following questions:

- What effluent quality (*i.e.* composition) can be achieved using UF/RO processes?
- What UF/RO technologies are needed for this preliminary design?
- What operating considerations are there?

To address the company's questions and concerns, WAVE can be used to determine the effectiveness and feasibility of using UF/RO membrane processes in order to treat the effluent water.

Be sure that you have installed the WAVE software before proceeding. We will use it—along with the information presented in this section—to design a UF/RO system to treat the brackish water.

Table 1.1: Water quality analysis (WQA) of the effluent water stream from the actual iron mine. The valuable iron has been removed in previous steps.

Property	**Value**
Average Temperature (°C)	15±7
Turbidity (NTU)	85.2
pH (@ 15°C)	7.52
Total Suspended Solids (mg/L)	80.9
Total Organic Carbon (mg/L)	11.2
Cationic Species	**Concentration (mg/L)**
Ammonium	1.56
Barium	0.065
Calcium	101
Magnesium	133
Potassium	25.7
Sodium	95.3
Strontium	0.875
Anionic Species	**Concentration (mg/L)**
Bicarbonate	83
Chloride	209
Nitrate	1.7
Sulfate	700
Neutral Species	**Concentration (mg/L)**
Boron	0.08
Silica	3.06

1.4 Setting Up the Simulation

Before we begin simulating the system at hand, we must set up a new project in Wave.

Setting the Display Units. To ensure that your results match the ones presented in these tutorials, we will ensure that we are using the same units of measurements. To do this, (or to set the default units) navigate to the *Configuration* tab in the top menu and click [More]. We will use metric units by default, and it is recommended that you choose "m^3/h" to match the influent flow rate given in Section 1.3. Verify your choice of units against the ones in Figure 1.3. Click [OK] when you are finished.

Specifying the Feed Water Quality In §1.3, we were given a WQA for the brackish effluent stream from the mine (*i.e.* Table 1.1). Now, we will input the data that we have into Wave. Begin by navigating to the *Feed Setup* tab in the top menu (or the *Feed Water* project tab). Then:

- In the *Feed Parameters* panel and under the *Water Type* and *Water Subtype* drop-down menus, select the categories which *best describe* your water source with regards to total suspended solids (TSS) and *turbidity*[1]. Here, we will choose "Wastewater" and "NTU ⩾ 30, TSS ⩾ 40" to match our WQA. This guides Wave in performing its calculations.
- In the *Solids Content* panel, we can specify the turbidity, TSS, Silt Density Index (SDI), and organics content (total organic carbon; TOC). Use the values from Table 1.1 to fill in these fields. This is with exception to the SDI (we do not have this value), so we can leave this field blank (*i.e.* 0 mg/L). All parameters in the *Solids Content* panel are *optional*.

[1]The turbidity or "cloudiness" of water is reported in the standard *Nephelometric Turbidity Units* (NTU).

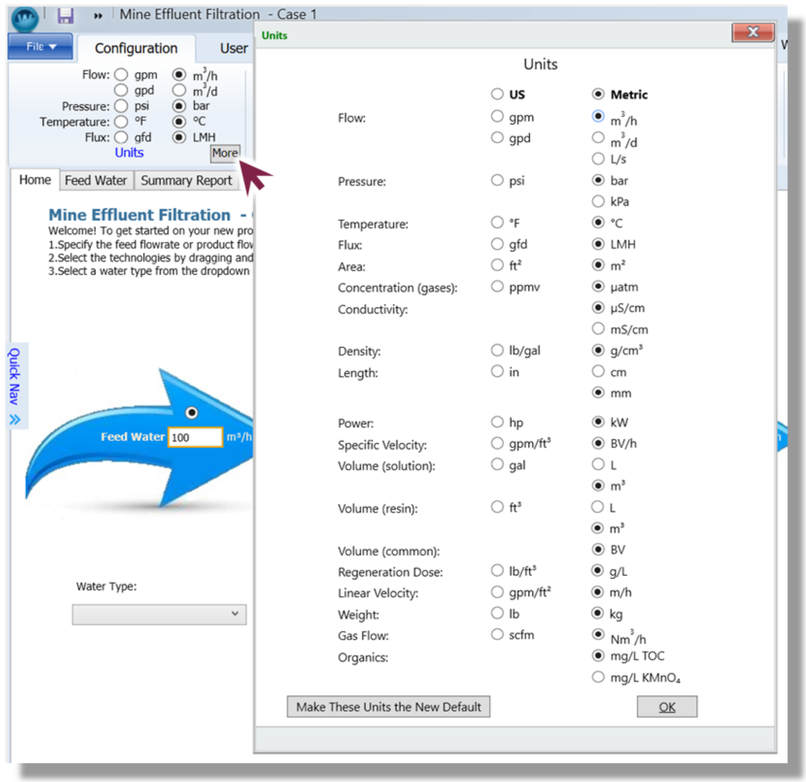


Figure 1.3: *Setting the display unit preferences for the* WAVE *simulation.*

- Beside the *Solids Content* parameters are fields for the system temperature and pH. Fill in these values from Table 1.1. The "minimum" and "maximum" design temperatures are the bounds between which the system should operate. We can use the variation on the temperature ($\pm 7^{\circ}$C) to populate these (albeit optional) fields.
- At the bottom of the screen, we can populate the tables of *Cations*, *Anions*, and *Neutrals* with values from Table 1.1. Be sure to use the columns with units of "mg/L". If a species is not specified in our WQA, leave that row blank (*i.e.* 0 mg/L).

Notice that several values *update* as you fill in the fields. For example, WAVE sums the total dissolved solutes, and estimates a solution conductivity. It also sums the total cations, anions and neutral species and calculates the overall "concentration of charge" (units: meq/L).[2] Even though we have not specified any carbon dioxide concentration, WAVE has updated this field to be a non-zero value due to chemical equilibria that exist in the water (*e.g.* bicarbonate $\rightleftharpoons$ carbon dioxide equilibrium) at a given pH and temperature.

> The calculations behind the water quality parameters (*e.g.* chemical equilibria) are quite complex; we will not delve into them in detail. Just be aware that WAVE performs calculations in the background to ascertain what exact chemical species are present, and in what concentration/activity.

Now at the bottom of the *Feed Setup* screen, note the "*Charge Balance*" value of approximately -0.97 meq/L. What do you think that this means if you have ~ 0.97 milli-equivalents of negative charge per liter? The interpretation of this value is that given the composition of salts/solids that we have specified to be in the water, the solution has an *overall (net) negative charge* equal to this value. Think of the net "milli-equivalent" of charge as being a milli-molar

[2] One mole of Na^{+} ions produces one equivalent (1 eq) of charge. One mole of Ca^{2+} ions produces 2 eq of charge. One mole of Cl^{-} ions produces -1 eq of charge.

excess of positive or negative ions. Our WQA analysis may not have detected additional cations in solution (*e.g.* residual Fe, Ni, etc.) that would balance out the negative charge. But we know that a solution cannot have an net charge: ions are always balanced by their counterions. As our solution has a *net negative charge*, we must "balance" it with *more positive ions*. In the software, we can do this by either (a) adding sodium ions, (b) adding calcium ions, (c) adding ammonia (ammonium) ions, or (d) adjusting the pH (adding H^+ ions). In our example here, we will balance the net charge by adding sodium ions. Using more sodium is unlikely to change critical results (*e.g.* fouling) as sodium salts are generally soluble over a wide range of process conditions. However, additional Na^+ ions may decrease the quality of our permeate water due to the small size and ability for these ions to cross RO membranes (as oppose to Ca^{2+}). Click Add Sodium on the menu bar to balance the charge with sodium ions. The charge balance should now be a very small value (approximately -0.000063 meq/L), which is essentially zero. The completed result is shown in Figure 1.4. We are ready to continue; return to the flow-sheet by clicking on the *Home* tab.

⚠ If you enter a water composition that is not charge-balanced, WAVE will not let you leave the *Feed Setup* screen until you make changes which set the net charge of the solution to zero.

As an aside, note that if you *do not* know much information about your feed water composition, WAVE offers a library of different water chemistries from all over the world. You can access them by clicking "*Open Water Library*" and selecting a suitable chemistry from the rather-extensive drop-down menu, as seen in Figure 1.5.

Specifying Desired Flow Rates. WAVE requires the user to specify *either* the total flow rate of the influent or effluent so that it can perform its calculations. In our scenario in §1.3, we were told that the mine produces 350 m^3/h of brackish wastewater. This is the influent flow rate to the treatment system. Ensure that the "*Feed Water*"

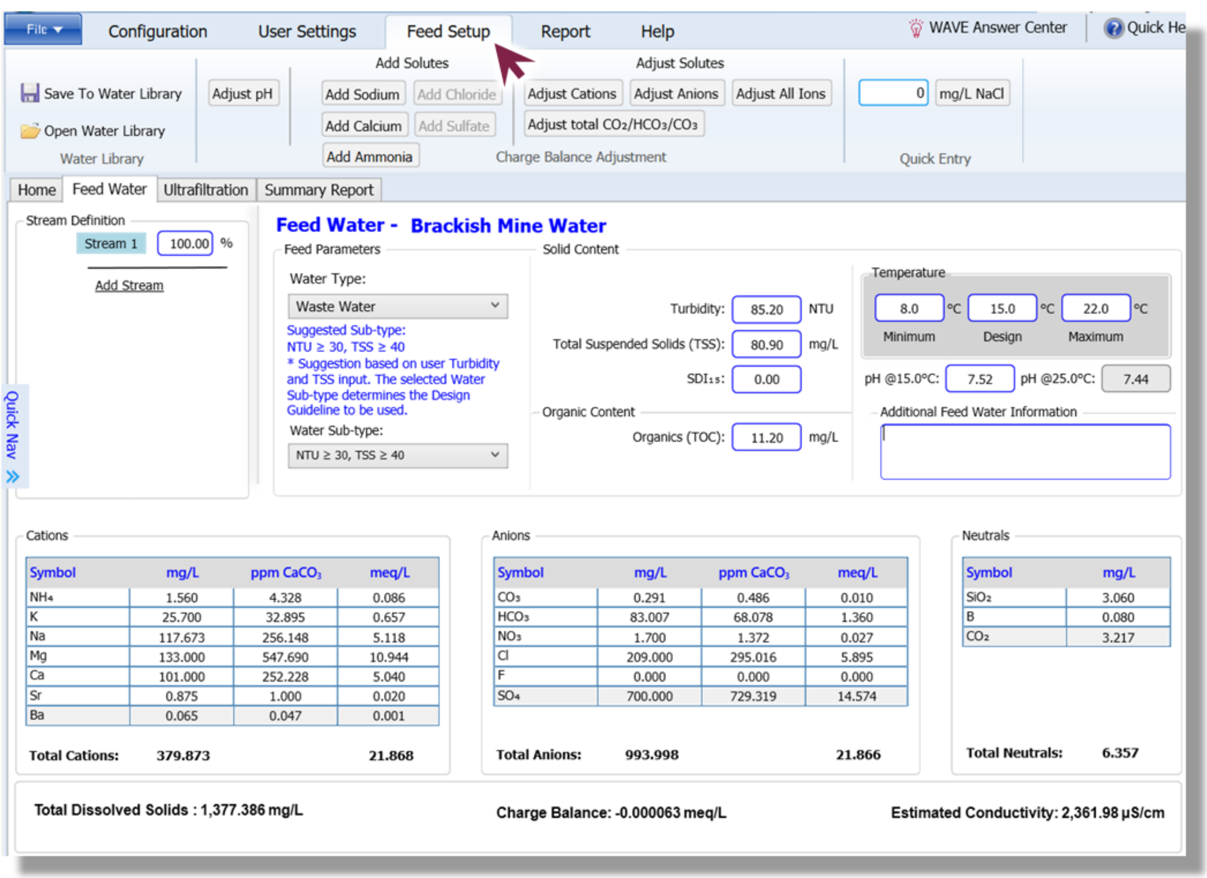


Figure 1.4: *Assigning water quality parameters to the brackish feed stream.*

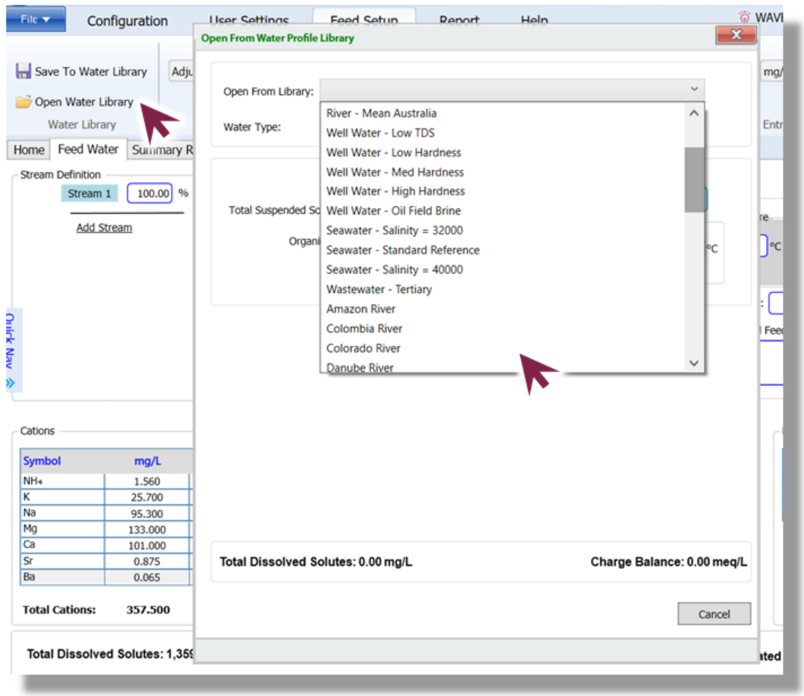


Figure 1.5: *You can select from pre-loaded water chemistries as a starting point.*

radio box (⦿) is ticked, and set the flow rate in the field below. Check that your units are correct! Your flowsheet should look like that shown in Figure 1.6. If we knew how much treated water that we needed to produce, we could set the flow rate of *Product Water* instead. We are now ready to add membrane processes to our system. Save your project before moving on to the next tutorial!

Ensure that you have properly defined the feed water composition before continuing onto the next section.

Figure 1.6: *Specifying the flow rate.*

End of Tutorial

Tutorial #2: Ultrafiltration Technologies in Wave

Tutorial #2 will consider the following concepts:

- The configuration of membrane processes
- Adding ultrafiltration processes to the flowsheet
- Assigning ultrafiltration operating parameters
- Interpreting summary report results and addressing design warnings
- Optimizing ultrafiltration processes

One of our separation process design heuristics says to "separate out the easiest-to-remove species first". Take another look at Table 1.1 from §1.3: what sorts of species are present in the water? What are the easy-to-remove contaminants in this feed water? In membrane filtration, the *largest* particles tend to be the easiest to remove. In our system, this would be the *suspended or colloidal* species: that is, the total suspended solids (TSS) and the turbidity. These particles are generally greater than ∼10 nm in size and may even exist in the micron size range. According to the "filtration spectrum", we could use a UF membrane in order to remove the colloidal matter first. This tutorial deals with the design and operation of UF membrane systems for the removal of suspended solids and turbidity.

ℹ UF systems are often used before RO membranes in order to remove colloidal matter which would otherwise foul the RO membranes!

Before we begin in detail, let us go through a few items of terminology that will be needed for this tutorial:

- **Module**: The smallest "membrane unit" in a UF process.
- **Skid**: A prefabricated assembly of modules, often mounted on a modular pallet. Depending on the manufacturer, modules within a skid can be arranged in sequence or in parallel (or a combination of both), depending on the requirements of the end user.
- **Train**: A complete self-contained arrangement of skids (or modules) with accompanying equipment (*e.g.* pumps, tanks, etc.) to meet treatment goals. Skids are arranged in sequence to meet separation quality objectives, while skids in parallel are used to meet capacity requirements. A plant often uses multiple parallel trains to further meet capacity *and* operability (*i.e.* maintenance, flexibility) needs.

Figure 2.1 illustrates the relationship between elements, modules, skids, and trains.

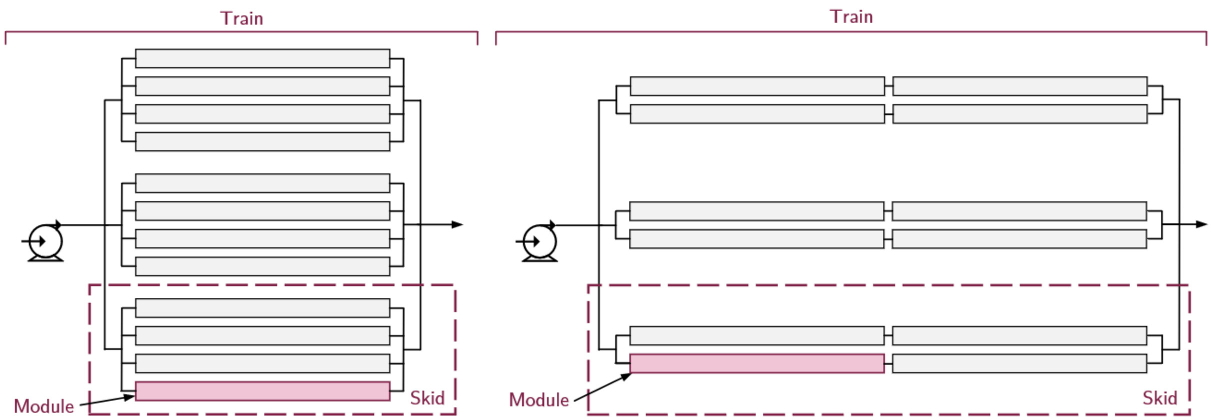


Figure 2.1: *Illustration of the relationship between modules, skids and trains. In this diagram, each skid has 4 modules, and each train has 3* parallel *skids with* $4 \times 3 = 12$ *modules. The left panel features* modules in parallel *within skids, while the right panel features* modules arranged both sequentially and in parallel *within a skid.*

2.1 Adding UF Membranes to the Flowsheet

Begin by navigating to the *Home* project tab; your empty flowsheet will be displayed. Locate the orange ultrafiltration icon in the *Technologies* panel. Drag and drop the icon onto the flowsheet, beside the feed arrow. A gray circle may appear when the UF icon has been dragged to the right location. Notice how a new *Ultrafiltration* project tab appears. You can modify the settings of the UF process here.

The UF process is now applied onto the flowsheet, seen in Figure 2.2. Unlike other software programs, Wave computes the results of the simulation automatically, after changes are made and before the simulation report is viewed. By adding the UF process to the flowsheet, Wave applies reasonable parameters for the system and immediately calculates a solution. We will now briefly learn how to modify the settings associated with the design and operation of the UF system.

2.2 Adjusting UF Process Settings

Navigate to the new *Ultrafiltration* project tab—the settings associated with adjusting your UF process can all be found here, as seen in Figure 2.3. On the left side of the screen, note the navigation tabs (*Design*, *Configuration*, *Backwash*, *CEB*, *CIP*, *Additional Settings*). The *Design* screen with Wave's default chosen settings is shown.

Components of a Membrane System. Let us go into further detail with regards to the parameters shown in the *Design* screen. Firstly, locate the *UF System Diagram* at the bottom left of the screen, which illustrates the different parts of the UF system train's design, including required equipment, flow rates, pressures, and concentrations. Let us go through the components of each train one-by-one:

Figure 2.2: *Adding a UF system to the flowsheet.*

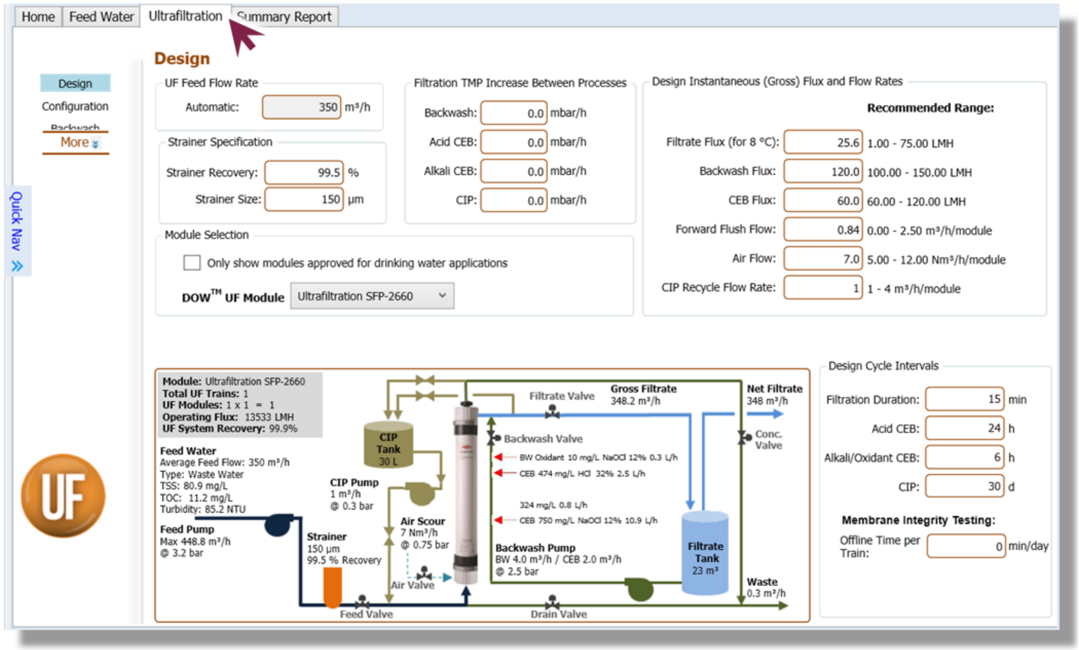


Figure 2.3: *Settings for the UF system can be heavily customized and adjusted.*

- **Strainer.** The strainer on the feed line is a coarse filter designed to remove large aggregates from the feed water before they can reach the membrane modules. This helps to prevent fouling and damage to the system. The size of the strainer mesh and its efficacy can be defined in the *Strainer Specification* panel above the diagram.

- **Membrane Module.** A depiction of a single membrane module is found in the center of the diagram. The specific membrane modules (and its internal elements) that you want to use in your design can be chosen from the *Module Selection* drop-down menu. Note that all the modules are manufactured by Dow!

For now, we will leave the membrane module as the *Ultrafiltration SFP-2660*. A product data sheet for this module can be found here: `https://www.lenntech.com/Data-sheets/Dow-UF-SFD-2660-L.pdf`.

- **Filtrate Tank.** A tank is positioned on the filtrate line leaving the membrane module. It acts as both a swing tank and as a reservoir for water with which to backwash the membrane. *Backwashing* is a frequent (*e.g.* every ∼ 15 mins) process by which foulants and debris on or inside the membrane structure are loosened and removed by forcing a short stream of water at high pressure backwards through the membrane (duration ∼ 1 minute). Backwashing parameters can be modified in the *Backwash* tab at the left of the screen. Also, a *chemically-enhanced backwash (CEB)* can be performed where a cleaning chemical (*e.g.* bleach, acid) is added to the backwash water in order to help scour and solubilize foulants and scale. Along with backwashing, CEB is a regularly-occurring process (∼ daily). These features are accessed in the *CEB* tab to the left of the screen.

- **Air Scour.** Like backwashing and other cleaning processes, air scouring is used to break up and clean out stuck-on solid debris accumulated within membrane modules. This process often occurs every few backwashes. Air scouring settings can be accessed under the *CEB* tab.

- **Cleaning-In-Place Tank.** This tank holds cleaning-in-place (CIP) chemicals dissolved in water. CIP is a occasional process (∼ monthly) whereby a membrane module or set of modules are taken offline and CIP solution is pumped into the modules to perform a very thorough cleaning of the entire membrane, such as for the removal of adhered foulants. These settings can be accessed in the *CIP* tab.

- **Pumps.** Several pumps (*e.g.* feed, backwash, CIP) are required in order to operate each membrane train. These flow rate values associated with these pumps are not for a single module or pump, but are the sum of the flow rates in all the trains (*i.e.* multiple pumps). While the diagram illustrates only one membrane module, the flow values are representative of the entire process.
- **Valves, Split & Mix Points.** The valves and split/mix points required to operate a single module are also indicated.

For now, we will leave the process settings at their default values. More on this to come!

The use of periodic backwashing, cleaning processes, and air scouring can help maintain the performance and health of the membranes. The frequency at which these processes are generally dictated by the propensity of the feed water to foul the membranes. These design cycle parameters—as well as the flow rates of air/water—can be tuned in their respective tabs, or in the *Design Cycle Intervals* panel and the *Design Instantaneous (Gross) Flux and Flow Rates* panel. Physical experimentation, simulation, literature searches, prior experience, and manufacturer knowledge all play a role in the complex process of choosing operational parameters, as well as the exact membrane manufacturer/module/membrane type/etc.!

ℹ To learn more about individual values on the screen, hover your mouse over the text. A tooltip will appear, when available!

The Configuration Screen. Now under the *Configuration* tab to the left side of the screen, you can choose the exact layout of the membrane system with regards to numbers of modules and trains, and modules per train. The WAVE software offers recommendations of configurations based on the water quality of your feed as well as the required flow rate. The suggested options can be seen in Figure 2.4. Notice that the total number of modules is quite consistent (492–506) even though the number of trains and modules per train varies. This is because the design requires a certain *total membrane area* in order to effectively treat the specified influent flow rate of water. This area is almost independent of the arrangement of modules into trains. Now, WAVE requires you to select one of the recommended configurations (or enter your own)—the "default" option is to have only one train and *one module*. Check out the *operating flux* in the *Selected Configuration* panel: 13,555 LMH (L/m^2/h).

How does this compare to the expected design flux for a single module? Check out the product data sheet at the link on page 11.

The calculated flux is massive and unreasonable as *all* of the water that we wish to treat is passing through a single module! At this point, we do not know what exact configuration of (multiple) modules/trains is best from a design or operational standpoint, so let us select a reasonable middle-ground option: Option 6, with 8 trains and 62 modules/train (496 total modules). Double-click on that row in the table to populate the *Selected Configuration* panel. Now the operating flux through a given membrane is 25 LMH—much more reasonable!

ℹ There is a cost tradeoff when choosing the number of trains and number of modules per train: each train tends to have its own pumping system and tanks for CIP/CEB. Increasing the number of trains increases the capital costs as you need more pump/tanks/piping/valves/etc. But, with more trains, you obtain greater operational flexibility (*e.g.* maintenance downtime) and perhaps a lower operational cost too.

Back on the *Design* screen, check out the gray box at the top-left of the *UF System Diagram*. The operating parameters have now been adjusted for our choice of configuration. In particular, note the *UF System Recovery* value: 62.2%. *What does this mean?* Consider the *Feed Water*, *Net Filtrate* and *Waste* stream flow rates on the diagram: approximately 62% of the feed water is filtered through the membrane and enters the filtrate stream. The other ∼38% is rejected to the waste concentrate stream. What does this mean in terms of the operation of the process? What happens to the ∼131.5 m^3/h of water that is "wasted"? Some other process must be used to deal with the rejected *concentrate* stream—perhaps a settling pond or a second UF process. At the end of this tutorial, we will attempt to improve the recovery of water.

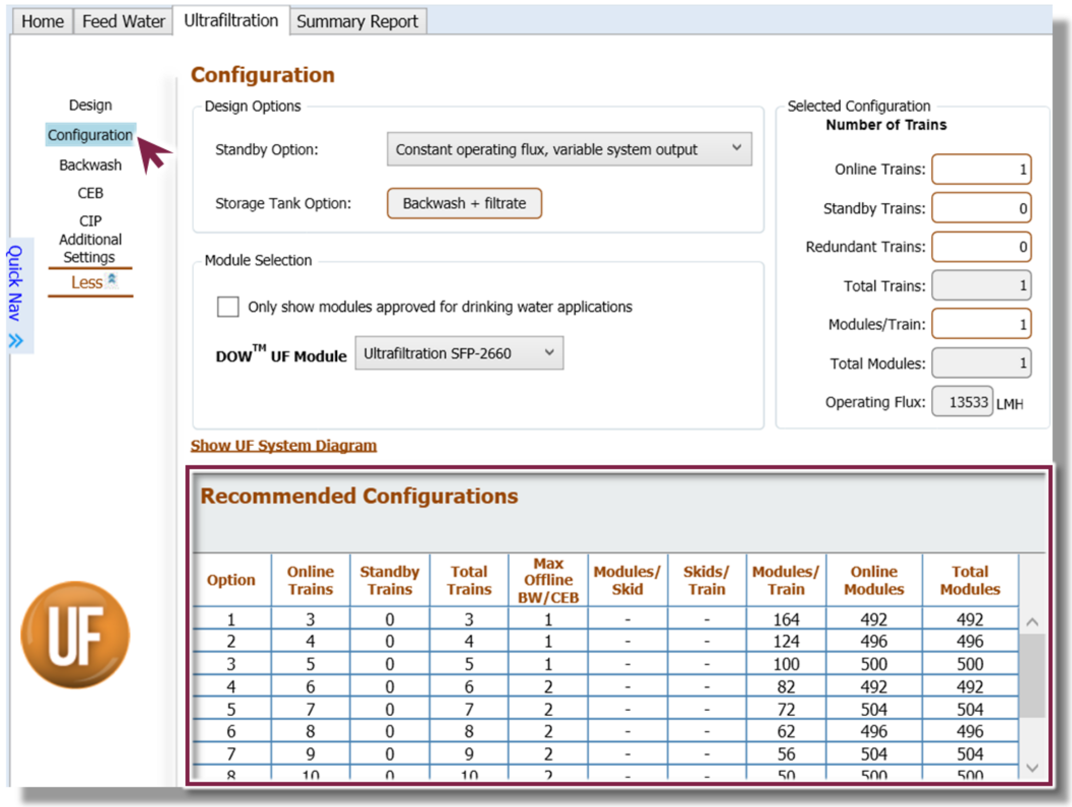


Figure 2.4: WAVE *suggests various configurations in terms of number of modules and number of modules per train.* WAVE *arranges the options in order of increasing number of trains and decreasing modules-per-train.*

2.3 Interpreting the UF Report

At this point, let us view the results from the simulation of the UF system, as it stands currently. Navigate to the "*Summary Report* tab in the project tabs. WAVE will now automatically calculate the remaining design and operation parameters from the information that has been provided to the software.

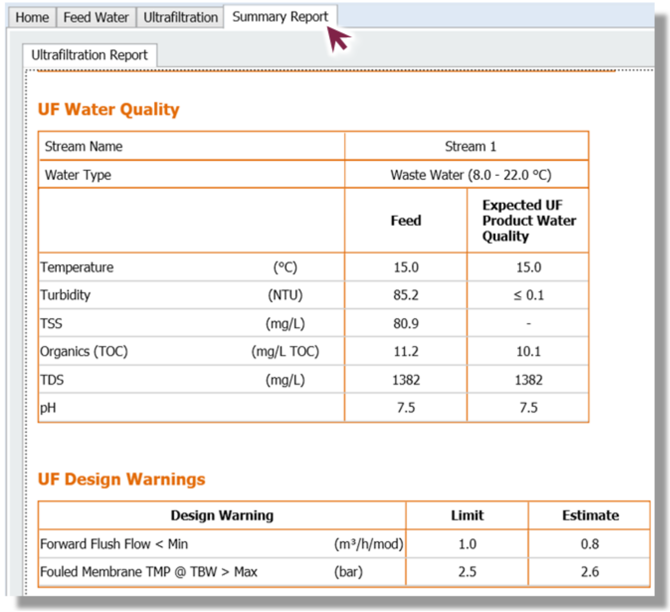
Like in other software packages, WAVE may at times display an error that the simulation cannot converge. This restricts you from viewing the summary report. If this is the case, ensure that your design parameters are as specified in this courseware. Otherwise, restarting the software can help to clear previous solutions from the software's memory and may enable convergence.

The *lower* section of the "UF Summary Report" is shown in Figure 2.5. WAVE divides the results into four categories: UF System Overview, UF Operating Conditions, UF Water Quality, and UF Design Warnings. Let us look at the last category to diagnose any issues associated with our design. Two warnings are present:

1. "Forward Flush Flow < Min": during the forward flushing membrane cleaning process, the flow rate (0.8 m^3/h/module) is less than the recommended value (1.0 m^3/h/module). We should increase the forward flushing flow rate manually.

2. "Fouled Membrane TMP @ TBW > Max": the transmembrane pressure at the time of backwashing starts (2.6 bar) is higher than design guidelines (2.5 bar). We need to reduce the TMP during backwashing.

To fix these issues, return to the *Ultrafiltration* tab and change the value of the "*Forward Flush Flow*" to 1 m^3/h/module on the *Design* view to dismiss the first warning. To deal with the elevated pressure during back-



Home | Feed Water | Ultrafiltration | Summary Report

Ultrafiltration Report

UF Water Quality

Stream Name		Stream 1	
Water Type		Waste Water (8.0 - 22.0 °C)	
		Feed	**Expected UF Product Water Quality**
Temperature	(°C)	15.0	15.0
Turbidity	(NTU)	85.2	≤ 0.1
TSS	(mg/L)	80.9	-
Organics (TOC)	(mg/L TOC)	11.2	10.1
TDS	(mg/L)	1382	1382
pH		7.5	7.5

UF Design Warnings

Design Warning		Limit	Estimate
Forward Flush Flow < Min	(m^3/h/mod)	1.0	0.8
Fouled Membrane TMP @ TBW > Max	(bar)	2.5	2.6

Figure 2.5: *A portion of the tabulated results for the simulation of the UF system, showing the provisional water quality results and design warnings.*

washing, we can reduce the flux of backwash water through the membrane: change the value of the "*Backwash Flux*" to 110 LMH from 120 LMH on the *Design* view. Return to the *UF Summary Report* and all warning messages should be gone. Observe the *UF Water Quality* table; see Figure 2.6.

- Turbidity has decreased from 85.2 NTU to less than 0.1 NTU.
- All of the TSS has been removed.
- The TOC content has decreased from 11.2 mg/L to 10.1 mg/L. The remaining TOC is most likely a dissolved fraction that passed through the UF membranes.
- Notably, the dissolved content (salts, small organics, etc.) remains unchanged at 1,382 mg/L! There is a need for a subsequent treatment process to remove these components.

Also note the results in the *UF System Overview* and *UF Operating Conditions* tables. Overall, our system has 8 trains producing an average product water flux of 20 LMH at an average TMP of 0.18 bar (15°C) and a net recovery of 64.3%. Each train creates 29 m^3/h of the total 223.9 m^3/h of permeate water produced by the UF system.

Now that we have learned some tools for the design and operation of UF systems, let us modify our current process to see if we can optimize the system in any way. But first, save your current project as it is—we will use it at the beginning of Tutorial #3.

UF Water Quality

Stream Name		Stream 1	
Water Type		Waste Water (8.0 - 22.0 °C)	
		Feed	**Expected UF Product Water Quality**
Temperature	(°C)	15.0	15.0
Turbidity	(NTU)	85.2	≤ 0.1
TSS	(mg/L)	80.9	-
Organics (TOC)	(mg/L TOC)	11.2	10.1
TDS	(mg/L)	1382	1382
pH		7.5	7.5

Figure 2.6: *Water quality report for the UF system (Dow SFP-2660) treating mining wastewater.*

2.4 Tutorial Questions

Consider the following open-ended scenarios in order to optimize the UF process. Each scenario builds upon the previous one. Attempt to mitigate any warning messages that Wave produces.

1. The permeate water recovery is low ($< 70\%$). Does Dow sell a UF membrane that would provide a better recovery? If so, replace the *Dow SFP-2660* with this membrane. Is the removal of turbidity/organics affected?
2. The current system configuration produces a constant flux, but a variable system water output (due to fouling). Realistically, the mining company would prefer a variable flux and a constant system output. This can be changed by choosing the "*Constant System Output, Variable Operating Flux*" option in the *Configuration* view. Remember to select a configuration from the table! Note that there are now *Standby Trains* in the design: trains that are only sometimes operational to "make up" additional capacity as the other membranes are taken offline for preventive maintenance (*i.e.* cleaning).
3. Does varying the total number of trains (including online plus standby trains) change the recovery of permeate water or the removal of solids?

For one particular scenario that was designed, two online trains (with one standby train) of *IntegraFlux SFP-2880XP* membrane modules were used, producing an average recovery of 67.09%. The TMP as designed was 0.2 bar at 15°C and the permeate water contained $\leqslant 0.1$ NTU of turbidity, 10.1 mg/L organics, and 1,382 mg/L of dissolved solids.

Also save your "optimized" treatment system as a *new file*. As everyone's optimization process will be different, we will use the previous unoptimized version at the beginning of the next tutorial for the sake of simplicity!

As organic molecules can vary widely in size and chemistry, the overall rejection of these organics in a UF system is very much dependent on the exact species which is/are present, as well as the membrane which is used. Thus the rejection calculation performed by Wave is very rough; the software recommends that you "tell" it the actual expected rejection of organics, determined via your own experiments. You can do this by right-clicking on the "*UF*" icon on the *Home* tab and selecting *Define Recovery*.

End of Tutorial

Tutorial #3:
Reverse Osmosis Technologies in Wave

Tutorial #3 will consider the following concepts:

- Simulating reverse osmosis systems
- The use of passes and stages
- Choosing reverse osmosis parameters
- Interpreting the results of the reverse osmosis simulation, including assessing error messages
- Optimizing the combined UF/RO system

In Tutorial #2, we "separated the easiest-to-remove species first" (the large colloidal species) through the use of UF membranes. If we look at the quality of the permeate water stream (*see* Figure 2.6), there is still significant amounts of solids left in the water, namely the *total dissolved solids* (TDS = 1,382 mg/L). In this tutorial, we will use RO membranes in order to reject the smaller "dissolved" species and produce highly-purified product water.

For clarification, the term "dissolved" in the context (*i.e.* versus *suspended* solids) does not literally mean that the particles themselves are actually dissolved, like salt ions. While a large fraction of "dissolved" solids are indeed ions, this category includes organic species which may be very small colloids, or are not by necessity solubilized!

Before we learn to simulate RO processes, let us consider a few additional pieces of terminology related to the arrangement of membranes in RO systems:

- **Element:** Like the *module* in UF system, an element is the smallest "membrane unit" in an RO process.
- **Pressure Vessel (PV)**: a container for one or more *elements* which are arranged in series.
- **Train:** Like UF processes, trains in RO systems are self-contained arrangements PVs with the necessary accompanying equipment (*e.g.* pumps, tanks, etc.).
- **Passes:** In a multiple-pass system within a train, permeate water from the first pass becomes the feed in the second pass, and so on. Passes are used to improve the permeate water quality.
- **Stages:** In a multiple-stage system within a train, the first stage retentate becomes the second stage feed, and so on. Stages are used to further purify concentrate water and/or obtain a greater water recovery.

An example of passes and stages can be seen in Figure 3.1.

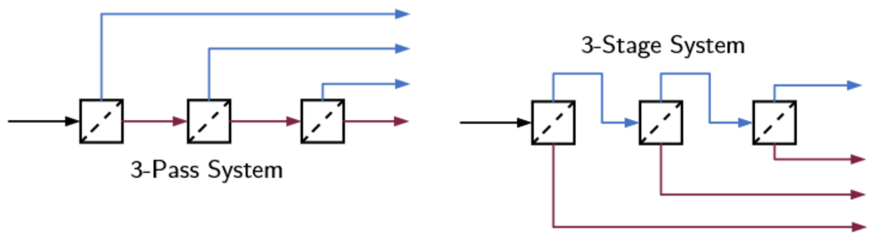


Figure 3.1: *Examples of 3-pass and 3-stage RO systems. Permeate streams are coloured in red, and concentrate streams are coloured in blue.*

3.1 Modelling RO Membranes

Following our UF process that we designed in Tutorial #2, we would like to install an RO system. That is, the permeate water from the UF process will feed into the RO system. To do this in the software, simply drag and drop the green "*RO*" icon onto the block-flow diagram (on the *Home* tab) right after the orange "*UF*" icon, as we did before. In this "default" configuration, WAVE assumes that the permeate water will flow into the next process as the feed. The results are shown in Figure 3.2.

As before, adding a reverse osmosis process to the flowsheet inserts a new tab in the *Project* tabs. Access the *Reverse Osmosis* tab to begin.

Figure 3.3 shows the initial screen whereby the user can adjust RO parameters. However, the default layout is for a single-stage, single-pass system. Features that can be modified include:

- **Pass Configurations.** At the top-left of the screen, you can specify parameters such as the number of stages in each pass.
- **Flows.** To the right of the pass configurations, WAVE displays the flow rates and fluxes present in that particular pass. Note that these values cannot be edited *independently*; they are the result of system constraints and calculations. You can manipulate the flows in some cases by clicking on any field. The *Reverse Osmosis Flow Calculator* dialog box is opened and you can then specify any bypasses (*i.e.* fraction of the feed that bypasses a stage/pass) and concentrate recycles (*i.e.* fraction of final concentrate stream which is recycled back to the beginning of the pass/module) to adjust your flow parameters.
- **Stage Parameters.** In the table at the bottom-left of the screen, the user can adjust parameters with regards to the system layout: the number of PVs per stage, the number of elements (EL) per pressure vessel, the exact Dow membrane element that is used, pressure parameters, and more.

In its default configuration, WAVE starts with a one-pass, one-stage design. To improve this design, let us consider the system that we have: ~224 m^3/h of permeate water containing mainly of dissolved solids (*i.e.* salts; ~1,400 mg/L). Assuming that the effluent discharge standards are not extremely strict, the "quality" of the permeate water is not too important. However, as we have a large volume of water to process and because we lost a significant fraction (~30%) during the UF step, we should process as much of the feed to the RO system as possible. Thus two design goals can be made:

Figure 3.2: *Adding an RO system to the flowsheet.*

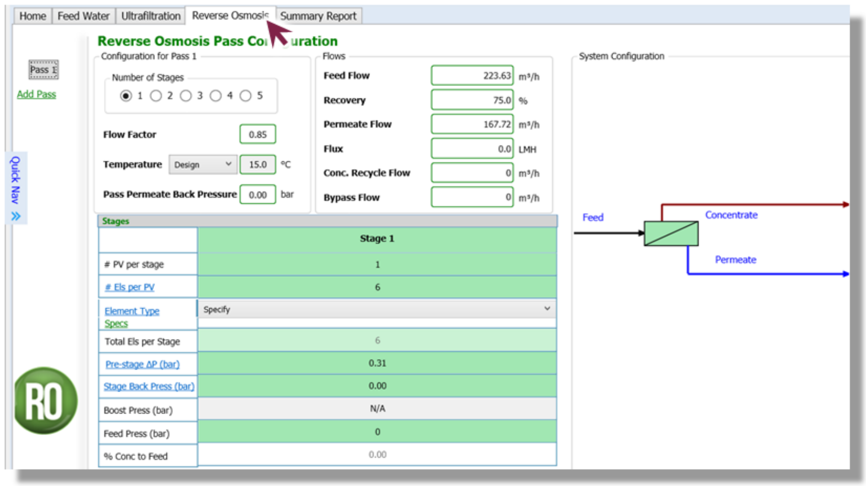


Figure 3.3: *Editing the design parameters for RO systems.*

1. As a high rejection of solids is not necessary, a minimum number of *passes* is acceptable.
2. As a high recovery of water is necessary, using multiple *stages* is advisable.

> ℹ While we are only using one pass in this design, the same process applies to all additional passes. Click "Add Pass" on the far left panel of the screen to increase the number of passes in a subsequent design.

With this in mind, begin by adding additional stages onto our first pass. Let us begin with *three* stages in the pass: Choose "3" stages in the *Configuration for Pass 1* panel. Note how the *System Configuration* diagram at the right of the screen updates to illustrate the three stages in the pass, as seen in Figure 3.4. We can now specify which exact membranes that we would like within the modules. WAVE allows the designer to use a different membrane type in each stage! For our system, let us return to the "perform the easiest separation first" heuristic:

- For the first stage, let us choose a more permeable membrane in order to create as much permeate water as possible before the feed water becomes saturated with salt. WAVE offers *nanofiltration membranes* (*i.e.* NF-series membranes) in addition to reverse osmosis membranes in its *RO* model. So for the first stage, select the "NF90-400/34i" membrane from the *Element Type* drop-down menu. The datasheet for this element can be found here: `https://www.lenntech.com/Data-sheets/Dow-Filmtec-NF90-400-34i-L.PDF`.
- For the subsequent two stages, let us choose RO membranes with good performance. Select the "XLE-440" membranes for these stages. The datasheet for this element can be found here: `https://www.lenntech.com/Data-sheets/Dow-Filmtec-XLE-440.pdf`.

> ℹ Clearly, the names of the membrane offerings from Dow do not tell us much about the properties and performance of the membranes. If you want to learn more about these membranes, click on the "Specs" link under the *Element Type* row label. Dow provides information such as the membrane's active area, element diameter (often 8 inches) recommended operating pressure, salt rejection rating in addition to other parameters.

Having selected our membrane types, we must tell WAVE how many pressure vessels (PVs) that we wish to have in each stage. In a real system, the number of PVs per stage would be the result of a complex optimization problem involving values such as water recoveries, operating costs, and plant footprint. For now, assign 20 PVs in each stage by typing the number into the "*# PVs per stage*" field in *each* stage. With 20 PVs in each of the 3 stages, and 6 elements per PV, the plant would have $20 \times 6 \times 3 = 360$ total RO elements. The number of *elements*

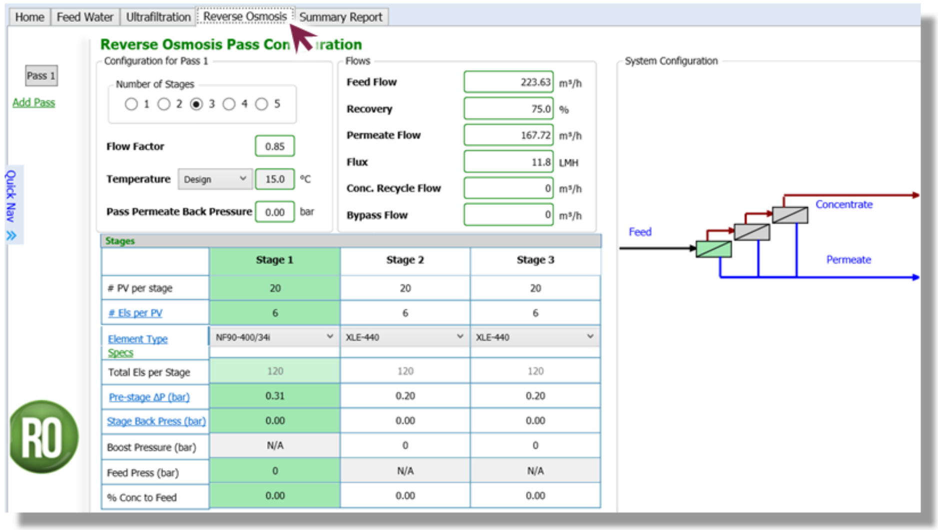


Figure 3.4: *The chosen design parameters for our three-stage, single-pass system.*

per PV is also assignable (< 8), but we will leave these values as default (6) for now. Check back to Figure 3.4 for the design parameters of our RO system.

Let us now run the simulation to determine the performance of our combined UF/RO system. Be sure that you check your parameters before you continue. WAVE's calculations often fail to converge—especially with RO systems—if there are incorrect parameters.

3.2 Interpreting the RO Report

When you are ready to proceed, click on the *Summary Report* tab again. Provided that your simulation converges, select the new *Reverse Osmosis Report* tab below. Much like the UF report, information on the performance of the system will be shown, including flow rates in each stream, pressures, recoveries, calculated ion concentrations, and results from each stage or pass. Let us work through the results in the report:

- **Summary Table.** In the first table (right below the process diagram), we have a summary of the flow conditions in the RO system, seen in Figure 3.5. Note that the RO feed from the UF trains enters the first pass at 223.8 m^3/h and 1,378 mg/L of dissolved solids (and at 5.3 bar), of which only 167.9 m^3/h leaves in the product stream (final TDS $\sim$ 60 mg/L)! The concentrate stream leaving the RO system on the other hand has a flow rate of 56 m^3/h with a very high TDS of $\sim$5,323 mg/L. Even though we are feeding 350 m^3/h of influent to the entire system, we are only producing 167.9 m^3/h in treated water (48% overall recovery). The rest of the water (UF, RO concentrate) must be purified via other technologies, or would be sent back to the tailings pond.

#	Description	Flow (m³/h)	TDS (mg/L)	Pressure (bar)
1	Raw Feed to RO System	223.9	1,377	0.0
2	Net Feed to Pass 1	223.8	1,378	5.3
4	Total Concentrate from Pass 1	56.0	5,323	2.5
6	Net Product from RO System	167.9	60.69	0.0

Figure 3.5: *Summary table for the RO process.*

> What is the separation factor (for TDS) of the RO system?

- **RO System Overview.** WAVE gives a summary of the design, configuration, and performance of the system in this table. Note a couple of key values: the recovery of the RO system is set (fixed) at 75%, the total active membrane area is 14,270 m^2, and the *specific energy* to treat this brackish feed stream is calculated as 0.25 kWh/m^3. Can you see how this value for the specific energy would be useful in designing this system?

> Verify that the average membrane flux in the RO system is equal to 11.8 LMH, the value in the table.

- **RO Flow Table (Stage Level)**. WAVE now summarizes a variety of flow/concentration parameters for each stage. You can use this table to determine if the design of each stage is adequate.
- **RO Solute Concentrations.** This table summarizes the concentration of each dissolved ion as a function of the stage, pass and stream. The table is reproduced in Figure 3.6. Note that in the concentrate streams, the ion concentrations increase with subsequent stages; as permeate water is filtered through the membranes, the larger salt ions remain behind in the concentrate streams. Similarly though, the concentration of ions in the permeate streams also increases with subsequent stages due to the *greater concentration driving force between the highly-enriched concentrate stream and dilute permeate stream.* However, it it should be noted that for all of the dissolved species, the RO system rejects the majority of the ions, leaving a well-purified permeate stream, as seen in the "*Total*" column of the permeate results.

> Note the relative concentrations of the species in the table—before and after the RO process. Some species are rejected to a higher degree (*i.e.* better retained in the concentrate) than others. Why do you think that this is case?

RO Solute Concentrations - Pass 1

Concentrations (mg/L as ion)

		Concentrate			Permeate			
	Feed	Stage1	Stage2	Stage3	Stage1	Stage2	Stage3	Total
NH_4^+	1.56	2.62	4.11	5.37	0.20	0.27	0.78	0.29
K^+	25.70	44.61	71.42	95.42	1.57	2.25	7.07	2.45
Na^+	117.7	204.5	327.7	438.5	6.92	9.79	30.58	10.70
Mg^{+2}	133.0	236.2	383.1	521.2	1.30	4.08	13.04	3.56
Ca^{+2}	101.0	179.4	291.0	395.9	0.96	3.06	9.84	2.67
Sr^{+2}	0.88	1.55	2.52	3.43	0.01	0.03	0.09	0.02
Ba^{+2}	0.07	0.12	0.19	0.25	0.00	0.00	0.01	0.00
CO_3^{-2}	0.29	0.94	2.40	4.21	0.00	0.00	0.00	0.00
HCO_3^-	83.00	145.6	233.4	313.9	2.01	3.99	12.61	3.89
NO_3^-	1.70	2.73	4.03	4.95	0.38	0.68	1.57	0.62
Cl^-	209.0	363.1	581.6	778.1	12.42	17.65	55.19	19.26
F^-	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
SO_4^{-2}	700.0	1,244	2,019	2,748	5.70	19.87	63.95	17.05
SiO_2	3.06	5.39	8.70	11.75	0.09	0.15	0.49	0.16
Boron	0.08	0.14	0.23	0.32	0.00	0.00	0.00	0.00
CO_2	3.22	3.51	4.09	4.73	3.26	3.65	4.22	3.50
TDS[a]	1,377	2,432	3,930	5,323	31.57	61.83	195.2	60.69
pH	7.5	7.7	7.8	7.8	6.1	6.3	6.7	6.3

Figure 3.6: *Calculated concentrations of dissolved species in each stage/stream of the RO system.*

- **RO Design Warnings.** WAVE issues design warnings when one or more calculated parameter (*e.g.* flow rates) is outside of the recommended design specifications. Like with the UF system, we have several design warnings, as seen at the top of Figure 3.7. Here, we can see that the flow rates of the concentrate streams in the second and third stages of the design are lower than the system limits. We will address this issue soon.
- **RO Flow Table (Element Level).** Like the table at the "stage level", WAVE summarizes the flow/concentration results for each element in the system.
- **RO Solubility Warnings.** Because RO systems tend to concentrate ions in the aptly-named "concentrate" stream, in some cases the ion concentrations can exceed the solubility limits of the species. WAVE attempts to warn the user here if that is the case. As is seen at the bottom of Figure 3.7, we have three warnings associated with exceeding the barium solubility limit (as barium sulfate). One such warning tells us that the saturation of $BaSO_4$ is above 100%. Barium is a notable problem in RO systems and even in tiny concentrations, it can cause problems as precipitated barium salts can deposit on the surface of the membranes and cause *mineral scaling*, which decreases the membrane flux over time. We will address this issue soon.

> What techniques can we use to prevent, mitigate, or treat barium sulfate scaling?

- **RO Chemical Adjustments.** If any chemicals such as pH adjusters (acids, bases), antiscalants, or dechlorinators are added, this table summarizes their effects on the system—good or bad. Now, notice that the $BaSO_4$ row is highlighted in red. This is WAVE's way of telling us that perhaps some chemical addition would help mitigate the effects of the supersaturated barium sulfate ions. Perhaps more interestingly, the barium ions were at $\sim$ 770% of the saturation limit even before the RO system. This value skyrockets to almost 4,000% in the concentrate from the first pass!

Addressing RO Warning Messages Now that we have perused the RO summary report, let us address the two warnings that WAVE has issued: the low concentrate flow rate in the second and third stages, and the supersaturation of barium sulfate in the feed/concentrates. Return to the *Reverse Osmosis* project tab, and consider the following actions:

- The concentrate flow rate is too low in many of the later pressure vessels. This can cause a problem because scaling or fouling is often mitigated by keeping the flow rate of water in the modules high. A high flow rate produces a high water velocity, which can "lift" scalant particles off the membrane's surface. One common way of increasing the concentrate flow rate (and water velocity) in RO systems is to actually recycle some of the final concentrate back to the feed of the RO system. This increases the flow rate of water over all the

RO Design Warnings

Design Warning		Limit	Value	Pass	Stage	Element	Product
Concentrate Flow Rate < Minimum Limit	(m^3/h)	4.09	3.84	1	2	6	XLE-440
Concentrate Flow Rate < Minimum Limit	(m^3/h)	4.09	3.60	1	3	1	XLE-440
Concentrate Flow Rate < Minimum Limit	(m^3/h)	4.09	3.39	1	3	2	XLE-440
Concentrate Flow Rate < Minimum Limit	(m^3/h)	4.09	3.21	1	3	3	XLE-440
Concentrate Flow Rate < Minimum Limit	(m^3/h)	4.09	3.05	1	3	4	XLE-440
Concentrate Flow Rate < Minimum Limit	(m^3/h)	4.09	2.92	1	3	5	XLE-440
Concentrate Flow Rate < Minimum Limit	(m^3/h)	4.09	2.80	1	3	6	XLE-440

RO Solubility Warnings

Warning	Pass No
Langelier Saturation Index > 0	1
$BaSO_4$ (% saturation) > 100	1
Anti-scalants may be required. Consult your anti-scalant manufacturer for dosing and maximum allowable system recovery.	1

Figure 3.7: *Warnings issued due to design and solubility violations in the RO system.*

stages, but also increases the TDS concentration due to the concentrated recycled salt solution! To recycle the concentrate stream back to the feed in WAVE, click any field in the *Flows* panel and set the "*Conc. Recycle*" field to be 35.00%, a value which should increase the concentrate flow rates in the modules just enough to suppress the warnings. The physical interpretation is that 35% of the final concentrate stream will be returned to the feed inlet, as seen in Figure 3.8. Make sure that the concentrate is recycled "*to the head of Pass 1*". Type Enter and then click OK when you are finished.

> What capital and operating cost implications are there if you recycle 35% of the final concentrate stream back to the feed of the RO system?

- The warning associated with the barium ions reflects the fact that barium ions and sulfate ions—of which we have a high concentration—react (almost) irreversibly to form insoluble barium sulfate which can scale the RO membranes. This scale is very difficult to remove. As such, we would like to minimize the scaling or decrease the barium saturation. Two potential solutions are to modify the pH of the RO feed to increase the solubility of the offending species, or by adding an anti-scaling chemical. For now, we will try the latter option. Under the *Configuration* tab, click the + Add Chemicals/Degas button. Click on the Anti-Scalant button to confirm that you are adding an anti-scalant to the RO feed; select sodium hexametaphosphate ($Na_6P_6O_{18}$) from the drop-down menu, and use the manufacturer's recommended dose of 3 mg/L. This can be seen in Figure 3.9. Click OK when you are finished.

Return to the *Reverse Osmosis Report* and check the *RO Design Warnings* and *Solubility Warnings*. You will notice that the concentrate recycle eliminated the design warnings, however the addition of the anti-scalant did not change the solubility warning. Barium is a persistent scalant, and even in the low concentrations that we see in this particular system, it can still cause issues. In some cases, feedwaters with barium may require a chemical precipitation step before using any RO membranes, or a cation exchange resin may also be used. At this time, we will ignore the barium saturation warning with the realization that other technologies may be needed to prevent or mitigate barium sulfate scaling.

> WAVE can model a cationic exchange resin to remove barium ions, but that is beyond the scope of this courseware.

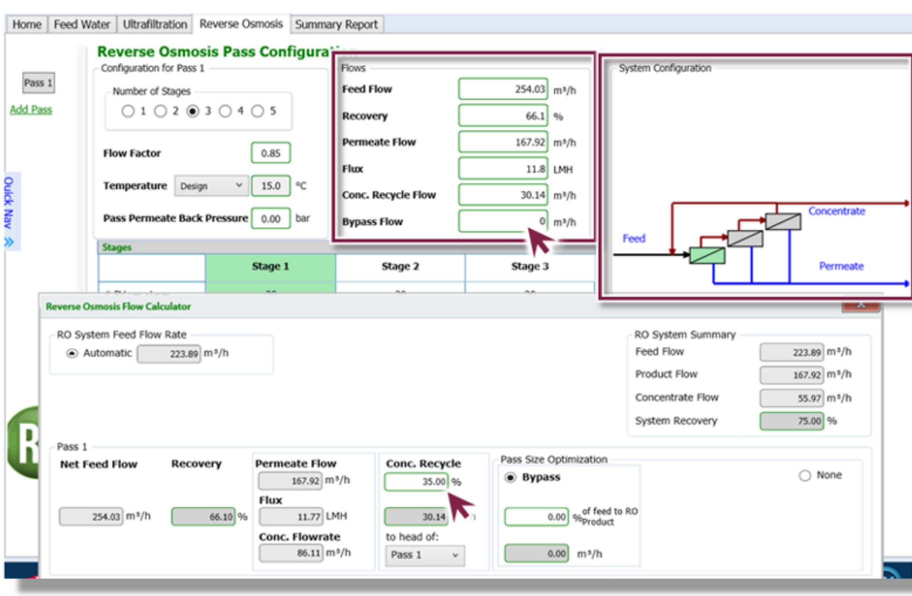


Figure 3.8: *Recycling a fraction of the final concentrate stream back to the feed to the RO system.*

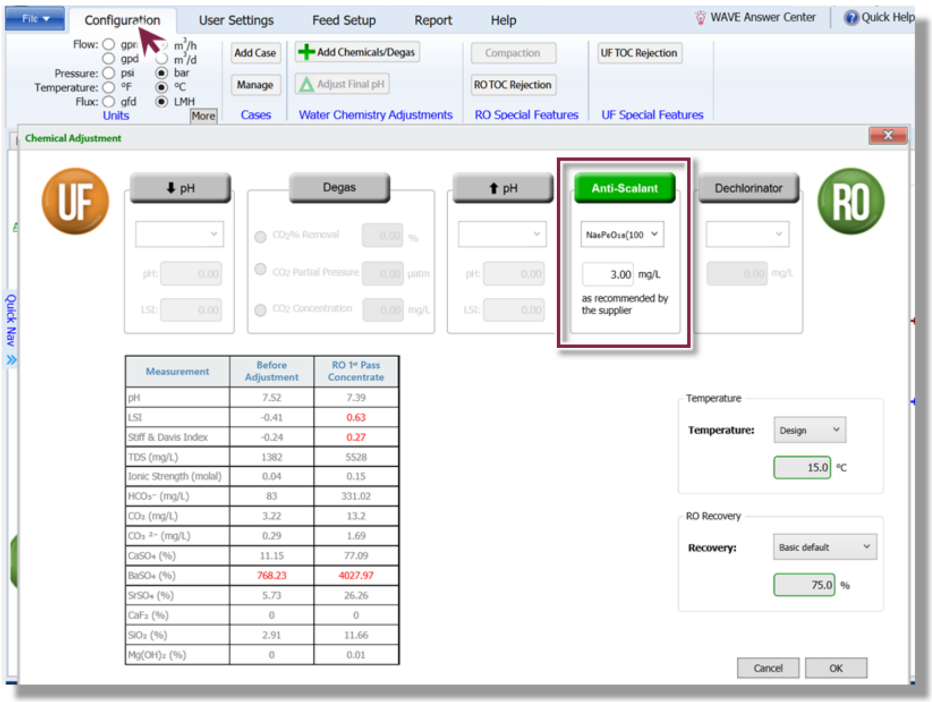


Figure 3.9: *Chemicals can be added to the RO feed water to adjust the water chemistry. Here, we add sodium hexametaphosphate as an anti-scalant.*

3.3 Tutorial Questions

Consider the following open-ended scenarios which will lead you in optimizing the combined UF/RO process. Each scenario can build upon the previous one; do not return to the original scenario with each question. Again, attempt to address any warning messages that WAVE produces. You may also attempt these scenarios/questions *in any order that you wish*. Just be aware that a subsequent question may undo a previous change that you have made, or cause new errors to be displayed.

> The WAVE software has a tendency of not being able to converge its calculations, especially when simulating RO systems. As a tip, when you make a change to system parameters and *it works*, save the system immediately. If a subsequent change makes a calculation fail to converge, but you undo that change, WAVE will sometimes fail to converge again! (WAVE may be using the non-convergent solution as an initial condition.) In this case, restart the software and return to the saved file. When in doubt, restarting the software clears previous values from the memory—especially those pesky non-convergent "solutions"!

1. At the end of Tutorial #2, you optimized your UF system. We returned to the unoptimized version so we all would be using the same results. Re-optimize the UF system. In particular, we want to engage the *standby trains* so that the UF process has a *constant system output, but variable operating flux*. Recall that this option is found in the *Configuration* view. You may need to adjust your RO settings to compensate for the increased flow rate (*e.g.* the number of PVs per stage).

2. By changing the membrane element type, can you improve the quality of the permeate stream, with all else equal?

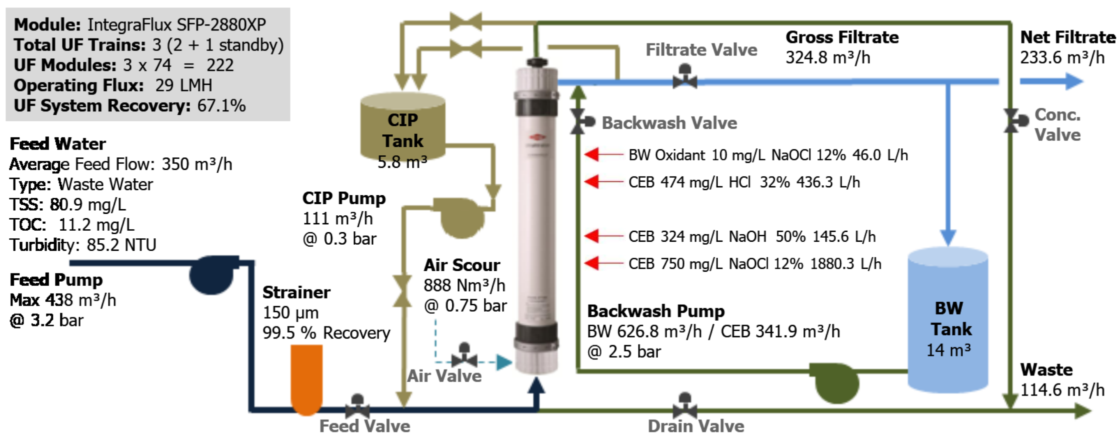
3. What is the effect of adding or removing a stage on the separation (*e.g.* the permeate quality, recovery, number of PVs/elements, etc.)?

4. Similarly, what happens if you add an additional *pass*? You can assume that the second pass is identical to the first, with the same number of stages, the same elements in each stage, the same number of PVs per stage, and so on.
5. In the simulation up until this point, we have used WAVE's default RO total recovery value (75%)—the fraction of the feed to the RO system that is recovered in the permeate stream. With your current system, can you increase the recovery percentage? What parameters do you have to modify to address any design warnings? Hint: the recovery can be adjusted by clicking on any field in the RO *Flows* panel, then adjusting the *System Recovery* value in the *RO System Summary* panel.
6. Can you reduce capital costs reducing the number of PVs required in each stage?
7. Just like we added an anti-scalant, add pH-adjusting chemicals to see if a different pH (higher or lower) can prevent the barium saturation warning.

At the end of this courseware, there is a PDF printout of the WAVE report for one particular UF/RO ”optimized” simulation. How is the same/different from yours? What features are included in this system?

End of Tutorial

UF Summary Report



UF System Overview

Module Type		IntegraFlux SFP-2880XP		
# Trains		Online = 2	Standby =	1
			Redundant =	0
# Modules		Per Train = 74	Total =	222
System Flow Rate	(m³/h)	Gross Feed = 350.0	Net Product =	233.7
Train Flow Rate	(m³/h)	Gross Feed = 175.0	Net Product =	116.8
UF System Recovery	(%)	67.09		
TMP	(bar)	0.25 @ 8.0 °C	0.20 @ 15.0 °C	
Utility Water		Forward Flush: Pretreated water	Backwash:	UF filtrate water
		CEB Water Source: UF filtrate water	CIP Water Source:	UF filtrate water

UF Operating Conditions

	Duration	Interval	Flux/Flow
Filtration:	15.0 min	18.9 min	-
Instantaneous			
2 Online Trains			29 LMH
3 Total Trains			19 LMH
Average			19 LMH
Net			14 LMH
Backwash	3.9 min	18.9 min	110 LMH
Acid CEB	16.7 min	24 h	60 LMH
Alkali CEB	16.7 min	6 h	60 LMH
CIP	312.9 min	30 d	1.50 m³/h
Membrane Integrity Testing	0.0 min	24 h	-

UF Water Quality

Stream Name		Mine Effluent	
Water Type		Waste Water (8.0 - 22.0 °C)	
		Feed	Expected UF Product Water Quality
Temperature	(°C)	15.0	15.0
Turbidity	(NTU)	85.2	≤ 0.1
TSS	(mg/L)	80.9	-
Organics (TOC)	(mg/L TOC)	11.2	10.1
TDS	(mg/L)	1382	1382

pH	7.5	7.5

UF Design Warnings

None

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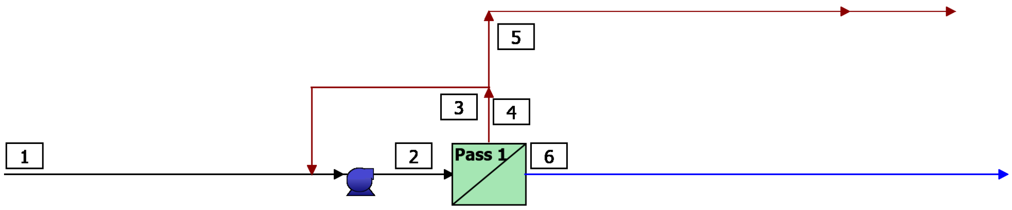
RO Summary Report

RO System Flow Diagram



#	Description	Flow (m^3/h)	TDS (mg/L)	Pressure (bar)
1	Raw Feed to RO System	233.7	1,377	0.0
2	Net Feed to Pass 1	240.9	1,531	6.2
3	Concentrate Recycle from Pass 1 to Pass 1	7.33	6,414	3.0
4	Total Concentrate from Pass 1	49.1	6,414	3.0
5	Net Concentrate from RO System	41.7	6,414	3.0
6	Net Product from RO System	184.6	37.01	0.0

RO System Overview

Total # of Trains	1	Online =	1	Standby =	0	RO Recovery	79.0 %
System Flow Rate	(m^3/h)	Net Feed =	233.7	Net Product =	184.6		

Pass		Pass 1
Stream Name		Mine Effluent
Water Type		Waste With DOW UF, SDI ≤ 2.5
Number of Elements		337
Total Active Area	(m^2)	13181
Feed Flow per Pass	(m^3/h)	240.9
Feed TDS[a]	(mg/L)	1,531
Feed Pressure	(bar)	6.2
Flow Factor		0.85
Permeate Flow per Pass	(m^3/h)	184.6
Pass Average flux	(LMH)	14.0
Permeate TDS[a]	(mg/L)	37.01
Pass Recovery		76.6 %
Average NDP	(bar)	3
Specific Energy	(kWh/m^3)	0.26
Temperature	(°C)	15.0
pH		7.5
Chemical Dose		
RO System Recovery		79.0 %
Net RO System Recovery		79.0%

Footnotes:

[a]Total Dissolved Solids includes ions, SiO_2 and $B(OH)_3$. It does not include NH_3 and CO_2

RO Flow Table (Stage Level) - Pass 1

Stage	Elements	#PV	#Els per PV	Feed				Concentrate			Permeate			
				Feed Flow	Recirc Flow	Feed Press	Boost Press	Conc Flow	Conc Press	Press Drop	Perm Flow	Avg Flux	Perm Press	Perm TDS
			PV	(m^3/h)	(m^3/h)	(bar)	(bar)	(m^3/h)	(bar)	(bar)	(m^3/h)	(LMH)	(bar)	(mg/L)
1	NF90-400/34i	20	8	240.9	7.33	5.9	0.0	98.4	4.8	1.1	142.6	24.0	0.0	38.34
2	ECO PLATINUM 440i	15	7	98.4	0.00	4.6	0.0	61.7	4.0	0.6	36.7	8.5	0.0	25.67
3	SW30ULE-440i	12	6	61.7	0.00	3.8	0.0	56.4	3.0	0.8	5.33	1.8	0.0	79.60

RO Solute Concentrations - Pass 1

Concentrations (mg/L as ion)

	Raw Feed	Adjusted Feed		Concentrate			Permeate			
		Initial	After Recycle	Stage1	Stage2	Stage3	Stage1	Stage2	Stage3	Total
NH_4^+	1.56	1.56	1.72	3.85	6.08	6.61	0.24	0.10	0.56	0.22
K^+	25.70	25.70	28.44	66.89	105.8	115.4	1.89	1.30	4.49	1.85
Na^+	117.7	117.7	130.3	306.9	486.7	531.1	8.37	3.98	17.75	7.77
Mg^{+2}	133.0	133.0	148.1	360.2	573.3	627.3	1.60	1.43	2.33	1.59
Ca^{+2}	101.0	101.0	112.5	273.6	435.5	476.5	1.18	1.07	1.76	1.18
Sr^{+2}	0.88	0.87	0.97	2.37	3.77	4.13	0.01	0.01	0.02	0.01
Ba^{+2}	0.07	0.06	0.07	0.18	0.28	0.31	0.00	0.00	0.00	0.00
CO_3^{-2}	0.29	0.29	0.37	2.15	4.99	5.84	0.00	0.00	0.00	0.00
HCO_3^-	83.00	83.00	92.07	219.3	343.7	374.2	2.44	4.37	13.58	3.14
NO_3^-	1.70	1.70	1.85	3.88	6.11	6.62	0.45	0.12	0.67	0.39
Cl^-	209.0	209.0	231.4	544.9	864.9	944.1	15.01	5.97	27.04	13.56
F^-	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
SO_4^{-2}	700.0	700.0	779.5	1,898	3,022	3,306	7.04	6.79	9.70	7.07
SiO_2	3.06	3.06	3.40	8.16	12.98	14.14	0.11	0.03	0.75	0.11
Boron	0.08	0.08	0.09	0.21	0.29	0.30	0.00	0.09	0.16	0.02
CO_2	3.22	3.22	3.22	3.95	4.97	5.24	3.36	4.23	5.03	3.58
TDS[a]	1,377	1,377	1,531	3,692	5,868	6,414	38.34	25.67	79.60	37.01
pH	7.5	7.5	7.6	7.8	7.8	7.8	6.1	6.3	6.7	6.2

Footnotes:

[a]Total Dissolved Solids includes ions, SiO_2 and $B(OH)_3$. It does not include NH_3 and CO_2

RO Design Warnings

None

RO Flow Table (Element Level) - Pass 1

Stage	Element	Element Name	Recovery (%)	Feed Flow (m^3/h)	Feed Press (bar)	Feed TDS (mg/L)	Conc Flow (m^3/h)	Perm Flow (m^3/h)	Perm Flux (LMH)	Perm TDS (mg/L)
1	1	NF90-400/34i	8.9	12.1	5.9	1,531	11.0	1.07	28.7	21.99
1	2	NF90-400/34i	9.2	11.0	5.7	1,678	9.97	1.01	27.2	25.37
1	3	NF90-400/34i	9.6	9.97	5.5	1,845	9.01	0.96	25.8	29.35
1	4	NF90-400/34i	10.1	9.01	5.4	2,037	8.11	0.91	24.5	34.10
1	5	NF90-400/34i	10.6	8.11	5.2	2,262	7.24	0.86	23.2	39.85
1	6	NF90-400/34i	11.3	7.24	5.1	2,526	6.42	0.82	22.0	46.93
1	7	NF90-400/34i	12.1	6.42	5.0	2,842	5.65	0.77	20.9	55.83
1	8	NF90-400/34i	12.9	5.65	4.9	3,224	4.92	0.73	19.6	67.31
2	1	ECO PLATINUM 440i	6.7	6.56	4.6	3,692	6.12	0.44	10.7	15.80
2	2	ECO PLATINUM 440i	6.6	6.12	4.5	3,954	5.72	0.41	9.9	18.43
2	3	ECO PLATINUM 440i	6.6	5.72	4.4	4,233	5.34	0.38	9.2	21.60
2	4	ECO PLATINUM 440i	6.5	5.34	4.3	4,529	4.99	0.35	8.5	25.43
2	5	ECO PLATINUM 440i	6.4	4.99	4.2	4,843	4.67	0.32	7.8	30.08
2	6	ECO PLATINUM 440i	6.3	4.67	4.2	5,172	4.38	0.29	7.2	35.73
2	7	ECO PLATINUM 440i	6.1	4.38	4.1	5,514	4.12	0.27	6.5	42.62
3	1	SW30ULE-440i	2.0	5.14	3.8	5,868	5.04	0.10	2.5	57.42
3	2	SW30ULE-440i	1.8	5.04	3.7	5,983	4.95	0.09	2.2	65.47
3	3	SW30ULE-440i	1.6	4.95	3.6	6,090	4.88	0.08	1.9	75.18
3	4	SW30ULE-440i	1.4	4.88	3.4	6,187	4.81	0.07	1.7	87.03
3	5	SW30ULE-440i	1.2	4.81	3.3	6,273	4.75	0.06	1.4	101.9
3	6	SW30ULE-440i	1.0	4.75	3.2	6,349	4.70	0.05	1.2	120.7

Footnotes:

[a]Total Dissolved Solids includes ions, SiO_2 and $B(OH)_3$. It does not include NH_3 and CO_2

RO Solubility Warnings

Warning	Pass No
Langelier Saturation Index > 0	1
$BaSO_4$ (% saturation) > 100	1
Anti-scalants may be required. Consult your anti-scalant manufacturer for dosing and maximum allowable system recovery.	1

RO Chemical Adjustments

	Pass 1 Feed	RO 1st Pass Conc
pH	7.5	7.8
Langelier Saturation Index	-0.41	1.19
Stiff & Davis Stability Index	-0.24	0.77
TDS[a] (mg/l)	1,377	6,414
Ionic Strength (molal)	0.04	0.18
HCO_3^- (mg/L)	83.00	374.2
CO_2 (mg/l)	3.22	5.24
CO_3^{-2} (mg/L)	0.29	5.84
$CaSO_4$ (% saturation)	11.2	95.3
$BaSO_4$ (% saturation)	768.2	4,872
$SrSO_4$ (% saturation)	5.7	31.6
CaF_2 (% saturation)	0.00	0.00
SiO_2 (% saturation)	2.9	13.4
$Mg(OH)_2$ (% saturation)	0.00	0.06

Footnotes:

[a]Total Dissolved Solids includes ions, SiO_2 and $B(OH)_3$. It does not include NH_3 and CO_2