

Desalination plant discharge calculator

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Abstract:

The impacts of a desalination plant discharge on the marine environment depend on the physical and chemical properties of the desalination plant reject streams, and the susceptibility of coastal ecosystems to these discharges depending on their hydrographical and biological features. Therefore, a good knowledge of both the effluent properties and the receiving environments is required in order to evaluate the potential impacts of desalination plants on the marine environment.

The brine flows are considerably large, generally up to 40 % (for membrane based technologies, like reverse osmosis, RO) and up to 90 % (for thermal technologies, like multi-stage-flash, MSF, including cooling water) of the intake flowrate. Thus either almost as large or even considerably larger flows than the required freshwater water flow. Salinity and temperature directly influence the density of the effluent. The various density differences between the brine and the receiving water represented by the buoyancy flux causes different flow characteristics of the discharge. The dense RO effluent flow has the tendency to fall as negatively buoyant plume and spread as a density current on the sea-floor. The effluent from thermal desalination plants is distinguished by a neutral to positive buoyant flux causing the plume to rise and to spread on the sea-surface.

This paper describes a discharge calculator to compute the effluent properties (i.e. density, flow, temperature, salinity, etc.) and substance concentrations at the discharge point. It allows the input of up to three different effluent types with different individual flows, properties and constituents, which are then merged at the discharge point. This allows the consideration of desalination effluents be blended with other effluents like treated wastewater or cooling waters from the process itself or a cogenerating power plant. Furthermore, the calculator characterizes the effluent properties and computes basic discharge characteristics by comparing the effluent properties with ambient characteristics. In addition, the calculator includes simple approaches to compute estimates regarding the initial mixing.

Results of computations for different case-studies demonstrate the potential of the calculator to estimate the order of magnitude of expected temperature, salinity or substance concentration at the discharge point and its surroundings. It allows furthermore to analyze the need for advanced discharge technologies which aim for enhanced effluent dispersion in the receiving environment and adequate discharge siting to avoid pollutant accumulation and to protect sensitive regions. It also allows to interpret the probability of interaction with the intake.

1 Introduction

Environmental impacts of sea water desalination plants are related to energy consumption and land use, but mainly to brine and cooling water effluent discharges into the marine environment (Einav, 2003). Sea water desalination plants carry a number of waste products into the coastal ocean (Lattemann and Höpner, 2003). The most direct product is a concentrated salt brine that may also have an elevated turbidity and temperature (latter most notable for MSF plants). Other waste products relate to chemicals used for biofouling control (chlorine), scale control (antiscalants), foam reduction, and corrosion inhibition. Furthermore, thermal desalination plant effluents are generally blended with considerably large flows of cooling water for the desalination process and/or cooling water from co-generating power plants, resulting in effluents with higher salinity and temperature and dissolved additives. The various resulting density differences between the brine and the receiving water cause different flow and dispersion characteristics of the discharge.

Thus, the fate of discharged substances and the related impacts of a desalination plant discharge on the marine environment depend on the physical and chemical properties of the desalination plant reject streams, and the susceptibility of coastal ecosystems to these discharges depending on their hydrographical and biological features. Effluent discharges are usually regulated by limiting pollutant levels in the reject streams at the point of discharge (effluent standards) and in the receiving environment (ambient standards). Furthermore, total allowable emission loads may be specified for certain pollutants, especially those if they have a tendency for accumulating in the environment, taking the pollutant concentration and the waste water flow rate into account. Therefore, a good knowledge of both the effluent properties and the receiving environments is required in order to evaluate the potential impacts of desalination plants on the marine environment.

Brine discharge systems need to be designed to minimize environmental impacts and costs while being in compliance with regulatory demands. A major principle before working on the brine discharge designs is to reduce the source concentrations and loads by proper mitigation measures within the desalination plant (e.g. reducing additive usage and dosing, improving plant efficiency, etc.) or proper intake and pre-treatment technologies. The second principle is the application of enhanced mixing technologies like multiport diffusers, sited in less sensitive regions (offshore, deep waters).

Once the plant design has been drafted first brine effluent characteristics should be computed within a screening approach. Those studies follow a very strong generalization and schematization, thus only allow for an order of magnitude analysis. However, one should not underestimate the value of such investigations during the planning phase and as a starting point for more detailed environmental impact studies and process modelling.

The here described screening calculators are all based on simplified but validated scientific theories. They are coded in Excel spreadsheets and illustrated with nomograms. The spreadsheet is named the discharge calculator and includes a density calculator, both of them described in the following sections.

2 Brine discharge characteristics

The discharge characteristics are defined by the characteristics of 1) the **built discharge structure**, such as the *type* of the discharge structure (open channel, submerged/elevated pipe, etc.), the *site* of the discharge structure (at the bank, in the water body, in the bay, close to breakwaters or groynes, etc.), the *dimensions* of the discharge structure (channel cross-section, pipe diameter, multiport installation, etc.), the *orientation* of the discharge structure (discharge angles relative to prevalent

currents or dominant geographical/bathymetrical features), and 2) the **effluent**, such as the *type* (municipal/industrial wastewater, combined overflow, drainage water, cooling water, desalination plant effluent), the *physical properties* (temperature, salinity, density, viscosity, etc.), the *fluxes* (volume and momentum flux resulting from flowrate and discharge velocities), the *chemical/biological properties* (substance/bacteria concentrations, etc.), the *loads* (yearly substance loads discharged).

The receiving water characteristics are defined by 1) the **local conditions** near the discharge site, such as the *type* of water body (river, lake, coast, etc.), the *topography* (meandering river, coastal bay, etc.), the *bathymetry* (slopes, shallowness, etc.), the *physical properties* (temperature, salinity, density, velocities, etc.), the *metereological/hydrological conditions* (flow, velocity and water level variations, density variations, reversing/non-reversing flows, etc.), the *chemical/biological properties* (background concentrations, water quality conditions, natural assimilation capacities, etc.), and 2) the **regional conditions** for the whole water body or parts of it, such as the *proximity to other pressures* (other discharges, morphological changes, dams, backwaters, etc.), the *proximity to sensitive aquatic ecosystems* (mangrove forests, salt marshes, coral reefs, or low energy intertidal areas and shallow coasts), the general *flushing characteristics* (residence times, exchange times).

Main problems arise due to the strongly limited mixing behavior in the receiving waters, which is significantly influenced by the effluent density, which is dominated by the varying effluent salinity and temperature. The various density differences between the brine and the receiving water represented by the buoyancy flux causes different flow characteristics of the discharge (Figure 1 and Figure 2). The dense RO effluent flow has the tendency to fall as negatively buoyant plume. The MSF effluent is distinguished by a neutral to positive buoyant flux causing the plume to rise. The impacts of these pollutants and brine characteristics on the marine environment can be manifold and are usually mitigated by technical measures.

One efficient measure are discharge technologies aiming for enhanced effluent dispersion in the receiving environment and adequate discharge siting to avoid pollutant accumulation, to protect sensitive regions and to utilize natural purification processes. Multiport diffuser outfalls designed as efficient mixing devices installed at locations with high transport and purification capacities are capable to reduce environmental impacts significantly (Figure 2). Two regions of impact are generally distinguished: the Near field and the far-field. The “near-field” of a sea outfall is governed by the initial jet characteristics of momentum flux, buoyancy flux, and outfall geometry as these influence the effluent trajectory and mixing. Flow features such as the buoyant jet motion and any surface, bottom or terminal layer interaction also take place. In the near-field region, outfall designers can usually affect the initial mixing characteristics through appropriate manipulation of design variables. As the turbulent plume travels further away into the “far-field”, the source characteristics become less important. Conditions existing in the ambient environment will control trajectory and dilution of the turbulent plume through buoyant spreading motions, passive diffusion due to ambient turbulence, and advection by the ambient, usually time-varying velocity field.

In total, the discharge plume and associated concentration distributions generated by a continuous efflux from a sea outfall can display considerable spatial detail and heterogeneities as well as strong temporal variability, especially in the far-field. This has great bearings on the application of any water quality control mechanisms or monitoring issues.

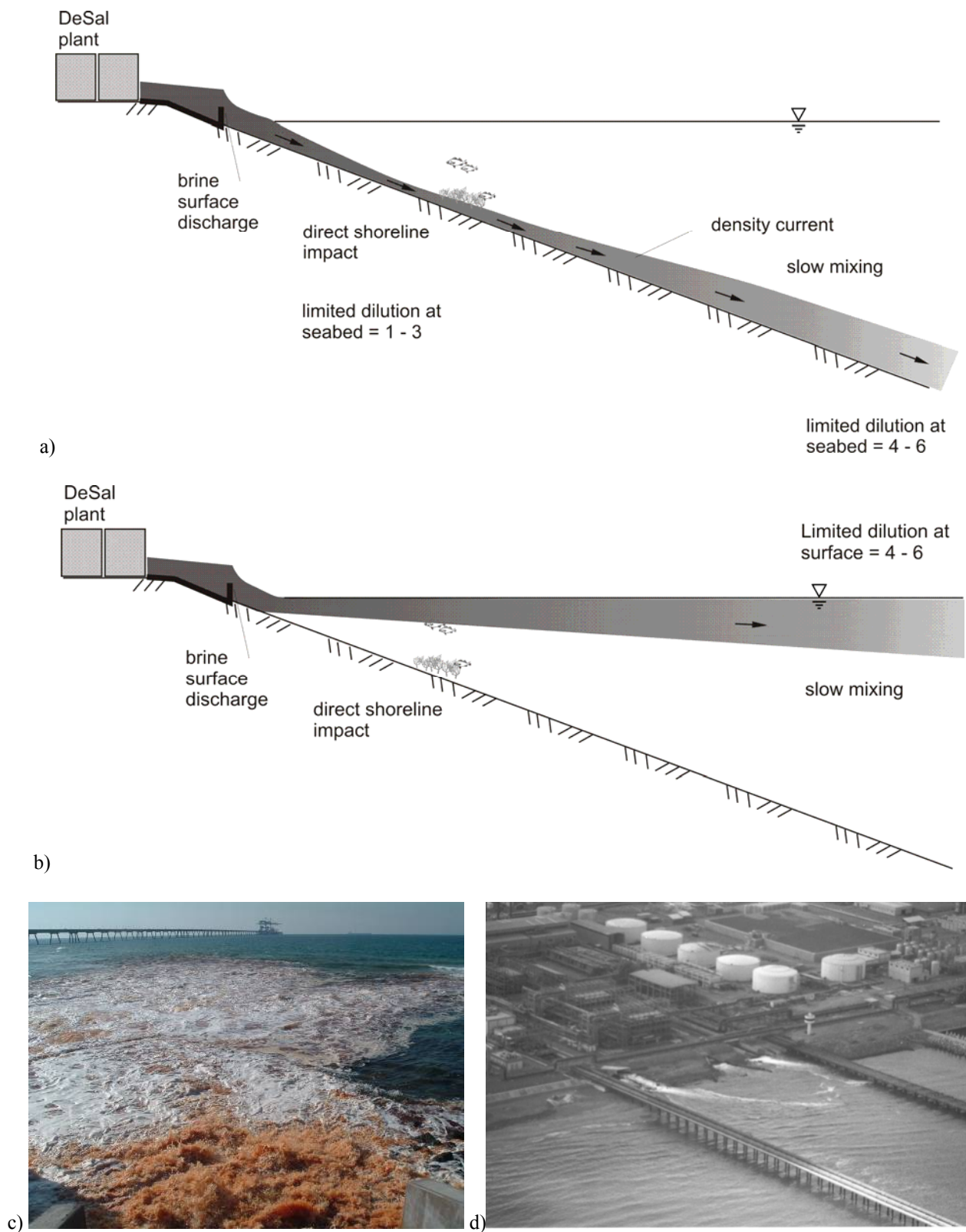


Figure 1: Mixing characteristics and substance distributions for shoreline brine discharge configurations via channel or weir: *a)* RO plant (dense effluent), *b)* thermal plant (dense effluent mixed with buoyant cooling water), *c)* shkelon RO desalination plant (Israel) showing dense brine discharge during backwash through an open channel at the coast into the Mediterranean (Courtesy S. Lattemann and T. Höpner), *d)* Al Ghubrah thermal desalination plant discharge through an open channel at the beach into the Gulf of Oman (photo: H.H. Al-Barwani)

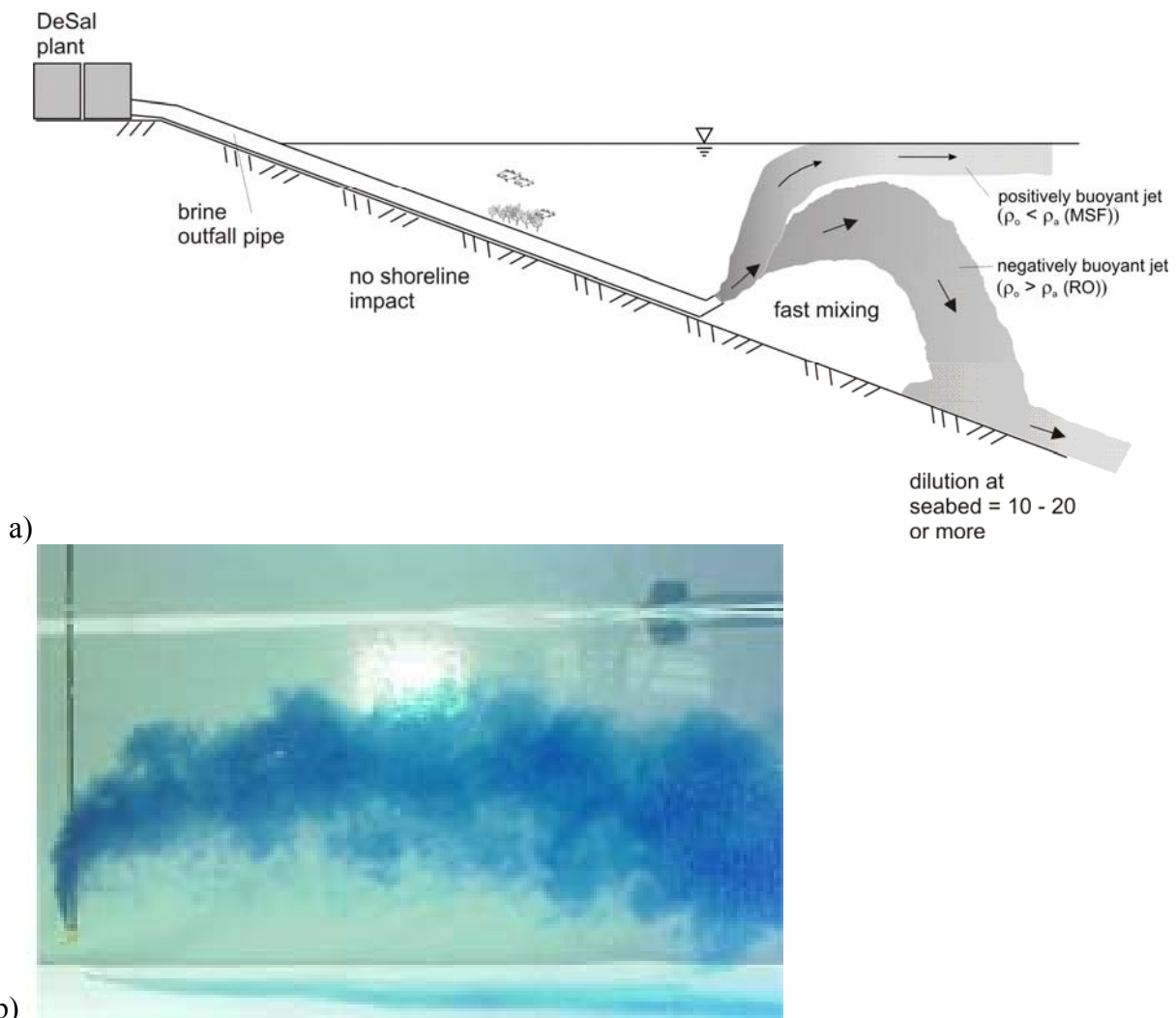


Figure 2: a) submerged discharge via pipeline and nozzle or diffuser shown for two effluent types: positively (thermal plant) and negatively buoyant (RO plant). b) Laboratory setup visualizing an optimized dense brine discharge resulting from a RO plant. Discharge is oriented 45° upwards, and advected by the ambient current from left to right, but still falling down the bed (Bandas, 2008).

3 Brine discharge design

The design of a discharge structure should follow the following general principles regarding:

1) The discharge siting, where the discharge location should be chosen in less-sensitive coastal regions. *No discharge permit* should be given for discharges which are planned in sites where direct and immediate impacts are to be expected, like in environmentally sensitive or even environmentally protected sites, like within or nearby coral reefs, in lagoons, in enclosed bays, within or nearby mangrove regions or similar places, or directly on shore or at beaches or at the shoreline. The discharge location should be chosen in coastal regions with good transport and flushing characteristics to avoid accumulation and allow for further mixing. *No discharge permit* should be given for discharges which are planned in sites with stagnant flows or enclosed, protected bays, like between structures for erosion protection or wave-breakers, lagoons, harbors, or very shallow waters with low current velocities.

2) The discharge design, where the discharge structure should be designed to avoid any direct or immediate impact with nearby boundaries. Therefore designs should be oriented into the open water body and not against the bed or the water surface, not cause strong bed or surface interactions, and

not be concentrated at one single point. The discharge structure should be designed to enhance effluent mixing. Therefore designs should allow for energetic discharges to allow for strong initial mixing, be oriented perpendicular or co-flowing to predominant ambient currents and optimally distribute the effluent within the water body.

The above design objectives can be met for offshore, submerged, multiport diffusers. The offshore location provides the necessary distance to sensitive region. Submerged discharges allow for improved mixing before interacting with boundaries and multiport diffusers guarantee enhanced mixing.. The above objectives should be considered for several siting and design alternatives to find optimal and cost-efficient solutions.

In order to demonstrate compliance with ambient standards (AS) for discharge permitting it appears that both dischargers as well as water authorities must increase the application of quantitative predictions of substance distributions in water bodies (water quality parameters in general, mixing processes in particular). This holds for both existing discharges (diagnosis) as well as planned future discharges (prediction).

There are several diagnostic and predictive methodologies for examining the mixing from point sources and showing compliance with AS-values:

Experiments. Field measurements or tracer tests can be used for existing discharges in order to verify whether AS-values are indeed met. **Hydraulic model studies** replicate the mixing process at small scale in the laboratory. They both are costly to perform and inefficient for examining a range of possible ambient/discharge interaction conditions.

Models. Mixing zone models are simple versions of more general water quality models. **General water quality models** may be required in more complex situations. They describe with good resolution the details of physical mixing processes (mass advection and diffusion), but the calculations are time intensive and expert knowledge is mandatory. Such studies are done once the plant draft has been developed and detailed environmental impact assessments considered.

Simple analytical equations or nomograms (e.g. Rutherford, 1994; Holley and Jirka, 1986) are often satisfactory to predict reliably the mixing behavior of a pollutant plume. They give very fast a first estimate about the discharge conditions and are very easy to handle, therefore especially useful for the design purpose of discharge structures.

4 SW Density and Viscosity Calculator

The most important brine property from the hydrodynamic viewpoint is the density and the density difference to the receiving waters, because density differences strongly influence the mixing and dispersion processes. The density of seawater, brine or freshwater itself is a function of salinity, temperature and pressure. The pressure influence is neglected in the following definitions, assuming applications already outside the desalination plant under normal atmospheric pressures. The calculator is programmed in a MS Excel spreadsheet and available for download under www.brinedis.net.ms.

The density calculator is based on El-Dessouky and Ettouny (2002) and is valid for salinities between 0 to 160 ppt and temperatures between 10 to 180 °C at pressures of $p = 1$ atm.

The density correlation is given by:

$$\rho = (A_1F_1 + A_2F_2 + A_3F_3 + A_4F_4) \cdot 10^3 \quad [\text{kg/m}^3]$$

where:

$$\begin{aligned}
 F_1 &= 0.5 & G_1 &= 0.5 & A_1 &= 4.032219G_1 + 0.115313G_2 + 3.26 \cdot 10^{-4}G_3 \\
 F_2 &= A & G_2 &= B & A_2 &= -0.108199G_1 + 1.571 \cdot 10^{-3}G_2 - 4.23 \cdot 10^{-4}G_3 \\
 F_3 &= 2A^2 - 1 & G_3 &= 2B^2 - 1 & A_3 &= -0.012247G_1 + 1.74 \cdot 10^{-3}G_2 - 9.0 \cdot 10^{-6}G_3 \\
 F_4 &= 4A^3 - 3A & & & A_4 &= 6.92 \cdot 10^{-4}G_1 - 8.7 \cdot 10^{-5}G_2 - 5.3 \cdot 10^{-5}G_3 \\
 A &= (2T-200)/160 & B &= (2Sal-150)/150 & & \text{with } T \text{ in } ^\circ\text{C} \text{ and } Sal \text{ in ppt.}
 \end{aligned}$$

The dynamic viscosity correlation of sea water is given by:

$$\begin{aligned}
 \mu &= \mu_W \cdot \mu_R \cdot 10^{-3} & [\text{kg}/(\text{ms})] \\
 \nu &= \mu / \rho & [\text{m}^2/\text{s}]
 \end{aligned}$$

where:

$$\begin{aligned}
 \ln(\mu_W) &= -3.79418 + 604.129/(139.18 + T) \\
 \mu_R &= 1 + A \cdot Sal + B \cdot Sal^2 \\
 A &= 1.474 \cdot 10^{-3} + 1.5 \cdot 10^{-5} T - 3.927 \cdot 10^{-8} T^2 \\
 B &= 1.0734 \cdot 10^{-5} - 8.5 \cdot 10^{-8} T + 2.23 \cdot 10^{-10} T^2
 \end{aligned}$$

Figure 3 shows a screenshot of the density calculator, which requires the input of temperature and salinity to compute the density using the above described equations. Figure 4 and Figure 5 show a nomogram for defining either the density or the viscosity for given salinity and temperature. Using those, no PC is needed for first estimates.

SEAWATER DENSITY & VISCOSITY CALCULATOR

Please enter the values of salinity and temperature of the effluent or ambient water (p=1atm):

Salinity: Sal = ppt

Temperature: T = °C

for ρ : $0 \leq Sal \leq 160$ ppt

for μ : $0 \leq Sal \leq 130$ ppt

$10 \leq T \leq 180$ °C

Density: ρ = kg/m³

Dynamic Viscosity: μ = *10⁻³ kg/m s

Kinematic Viscosity: ν = *10⁻⁶ m²/s

Source:
El-Dessouky, Ettouney (2002): Fundamentals of Sea Water Desalination (Appendix A: Thermodynamic Properties)

Figure 3: Screenshot of density calculator (download under: www.brinedis.net.ms)

There are different formulas for density calculation given in literature (eg. UNESCO Technical Papers) and online (eg. www.csgnetwork.com/h2odenscalc, www.phys.ocean.dal.ca/~kelley/seawater/density.html). Since UNESCO uses different equations for different ranges of salinities and temperatures, the equation of El-Dessouky and Ettouney (2002) have been chosen, covering a major range of salinities (0to160ppt) and temperatures (10to180°C) with only one equation. However, the available equations are giving different results. A comparison with two other calculating possibilities is shown in Figure 6. The calculations are based on:

- A. the SW Density & Viscosity Calculator ($Sal = 0-160$ ppt, $T = 10-180$ °C, $p = 1$ atm)
- B. the UNESCO equations

- $Sal = 0 - 42$ ppt, $T = -2 - 40$ °C, $p = 1$ atm, following UNESCO (1981)
- $Sal = 42 - 50$ ppt, $T = 10 - 35$ °C, $p = 1$ atm, following UNESCO (1991)

C. the “Water Density Calculator” (<http://www.csgnetwork.com/h2odenscalc.html>)

No formula is not specified and no restrictions are made.

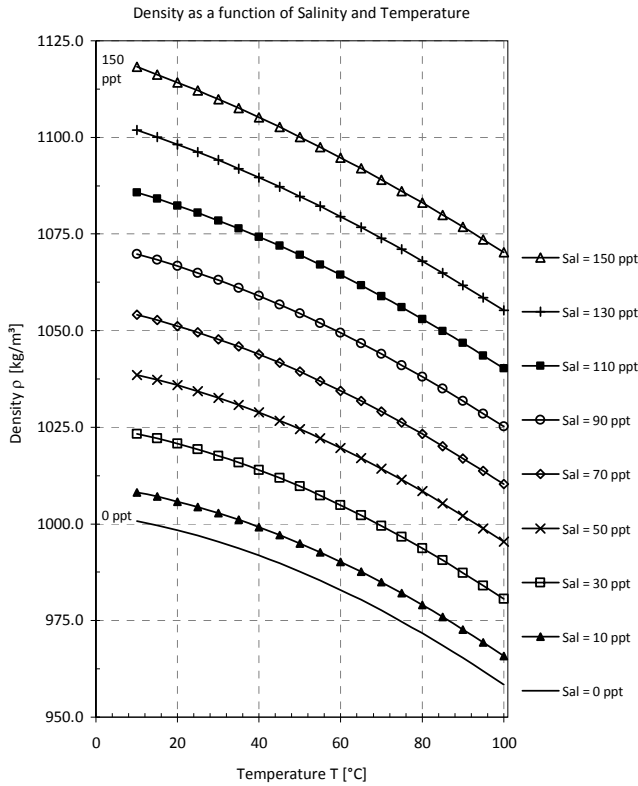


Figure 4: Nomogram for defining the effluent or seawater density for different salinities and temperatures

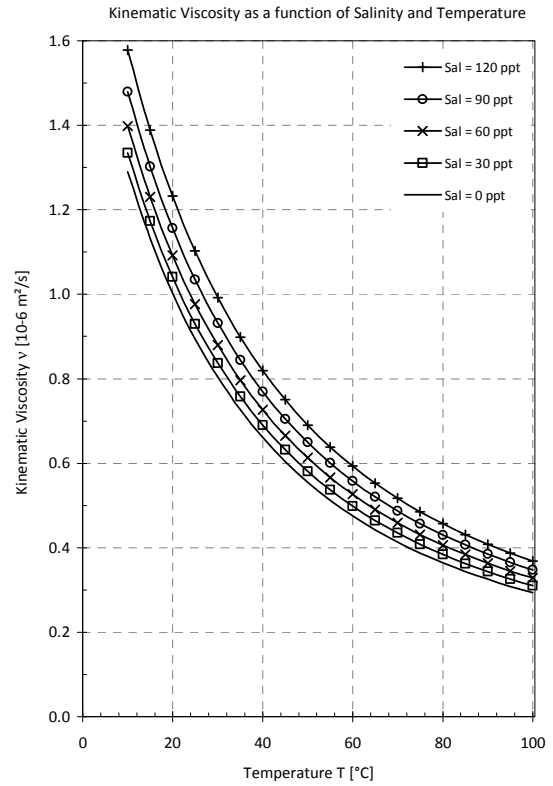


Figure 5: Nomogram for defining the effluent or seawater viscosity for different salinities and temperatures

The values are always computed for the water surface ($p = 1$ atm), since density is dependant on the pressure. The UNESCO equation of state consider the water depth ($p = 0$ to 1000 bar) for salinities in the range of 0 to 42 ppt and temperatures in the range of -2 to 40°C.

	Sal (ppt)	T (°C)	ρ [kg/m³]		
			A	B	C
1	0	20	998.402	998.206	998.234
2	10	20	1005.810	1005.793	1005.820
3	20	20	1013.263	1013.362	1013.389
4	30	20	1020.761	1020.954	1020.981
5	42	30	1026.621	1026.988	1027.015
6	45	30	1028.874	1029.221	1029.276
7	45	35	1027.053	1027.375	1027.428
8	45	36	1026.672	-	1027.039
9	50	35	1030.800	1031.038	1031.180

A: SW Density & Viscosity Calculator (El-Dessouky/Ettouney)

B: UNSECO equations

C: water density calculator (csgnetwork.com)

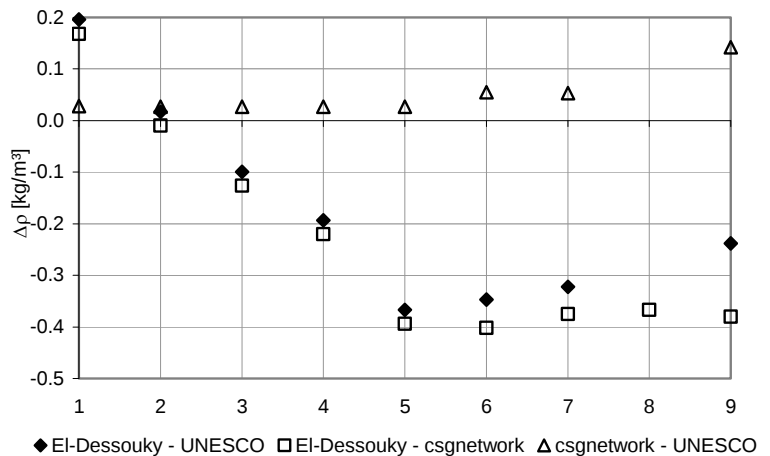


Figure 6: Differences in density calculation between different calculators for varying salinities and temperatures.

The comparison shown in Figure 6 show clear differences of the order of 0.3-0.4 kg/m³ especially for higher salinities. For most applications these differences, which are of the relative order of per thousands can be neglected. However, for all applications dependent on density differences, those small variations may cause significantly different results. This is especially true for environmental hydrodynamic mixing and transport processes, which are very sensitive to density differences. Further investigations will be necessary on one hand to further examine the reason for the inaccuracies in the mentioned equations. On the other hand, sensitivity analysis is recommend to account for the natural variation and the formulation inaccuracies in those terms.

5 Discharge calculator

The discharge calculator computes the effluent and general ambient properties at the discharge point. The results are used to interpret the discharge situation. Two calculators have been developed. One for dense discharges, called RO-discharge-calculator, which also includes an estimation of the near-field / initial dilution in the near-field for very simplified conditions. The other for thermal discharges, called MSF-discharge-calculator which includes an estimator for the initial dilution. The calculators are programmed in a MS Excel spreadsheet and available for download under www.brinedis.net.ms.

5.1 Effluent characteristics

Figure 7 and Figure 8 show the first table of the discharge calculators to define the final effluent characteristics. Yellow boxes indicate where user-input is necessary. The other boxes are computed and updated automatically.

Ambient characteristics

First the user needs to define the ambient temperature and salinity, which is the average coastal water temperature and salinity at the intake location. Thus, temperature and/or salinity variations and their effect on the discharge characteristics can easily be investigated by trying different temperature and/or salinity values and comparing their effects. The calculator then automatically computes and updates the related density and viscosity in the boxes below, using the embedded density calculator.

Drinking water (permeate) characteristics

The desired permeate flow has to be defined, as well as the recovery rate, defined as the total permeate flow divided by the total intake flow. For thermal desalination plants the recovery rate is related only to flow without considering the cooling water (which will be added later), so just to the desalination process. The calculator then automatically computes the necessary intake flowrate and the brine flowrate using mass-balance equations.

Concentrate characteristics

The calculator only needs the input of the concentrate temperature (usually only slightly above the intake water temperature for RO and rather high for MSF) to compute the concentrate characteristics. The calculator then computes the concentrate salinity and density automatically. Furthermore, the calculator allows to define an additional substance concentration (one for RO, three for MSF) to consider additive (flocclulants, anti-scalants, chlorine) usage and dosage and studying the effect of different concentration values on the final effluent characteristics.

Blended effluents

The calculator allows the input of up to one (RO) or two (MSF) different additional effluents, which are merged at the discharge point. This is to allow the consideration of effluents from the

desalination plant blended with other effluents like treated wastewater or cooling waters from the process itself or a cogenerating power plant. Those effluents have to be specified by giving the flowrate, temperature and salinity, and if applicable, additive substance concentrations related to the substances considered for the concentrate.

Flowrates & Effluent Characteristics RO

- ambient characteristics

ambient temperature	$T_a =$	20.00	°C
ambient salinity	$Sal_a =$	33.00	ppt
ambient density	$\rho_a =$	1023.02	kg/m ³
ambient kin. viscosity	$\nu_a =$	1.05E-06	m ² /s

annotations:

$T = 10$ to 180°C

$Sal = 0$ to 160 ppt (ppt = g/kg)

allowed ranges for viscosity calculation:

$Sal = 0$ to 130 ppt, $T = 10$ to 180°C (El-Dessouky, Ettouney (2002))

- drinking water (permeate)

flowrate	$Q_{drink} =$	6.00	m ³ /s
recovery rate	$r =$	50	%
intake flowrate	$Q_{in} =$	12.00	m ³ /s

recovery rate:

percentage of intake water converted into permeate;

plant characteristic; following Lattemann: $r = 40$ - 65%

- brine characteristics (effluent from desalination process)

plant effluent flowrate	$Q_{desal} =$	6.00	m ³ /s
temperature	$T_{desal} =$	20.00	°C
salinity	$Sal_{desal} =$	66.00	ppt
density	$\rho_{desal} =$	1048.12	kg/m ³
substance concentration	$C_{desal} =$	20.00	ppm

ambient or 1°C above

with $Sal_{drink} = 0$ ppt

e.g. coagulants, anti-scalants,

- blended effluent - external - (e.g. waste water or others)

flowrate	$Q_{effl,ex} =$	5.00	m ³ /s
temperature	$T_{effl,ex} =$	20.00	°C
salinity	$Sal_{effl,ex} =$	8.00	ppt
density	$\rho_{effl,ex} =$	1004.33	kg/m ³

$Sal = 0$ to 160 ppt, $T = 10$ to 180°C

Final effluent characteristics:

flowrate	$Q_o =$	11.00	m ³ /s
effluent temperature	$T_o =$	20.00	°C
effluent salinity	$Sal_o =$	39.64	ppt
effluent density	$\rho_o =$	1028.03	kg/m ³
buoyant acceleration	$g_o' =$	-0.04804	m/s ²
-> negatively buoyant, ok!			
kin. viscosity	$\nu_o =$	1.06E-06	m ² /s
substance concentration	$C_o =$	10.91	ppm

mean average

mean average

$g_o' = g * (|\rho_o - \rho_a|) / \rho_a$

$g_o' < 0$: negatively buoyant, $g_o' > 0$: positively buoyant

allowed ranges for viscosity calculation:

$Sal = 0$ to 130 ppt, $T = 10$ to 180°C (El-Dessouky, Ettouney (2002))

Figure 7: First table of RO-discharge-calculator to compute the final effluent characteristics

Results - Final effluent characteristics

Results are the final effluent flowrate, the effluent temperature and salinity, and the resulting density and viscosity and substance concentrations. In addition the calculator computes the buoyant acceleration defined as:

$$g_o' = g (\rho_o - \rho_a) / \rho_o$$

with g = earth acceleration, ρ_o = effluent density at discharge point, ρ_a = ambient density. The buoyant acceleration is a measure for density induced motions. The effluent is positively buoyant for positive g_o' and negatively buoyant (sinking down) for negative g_o' . In case of MSF, the final plant characteristics as the feedwater flowrate, the recovery rate (whole plant), and the temperature difference between the effluent and ambient water are estimated.

Flowrates & Effluent Characteristics MSF

- ambient characteristics (= intake water)

ambient temperature	$T_a =$	20.00	°C
ambient salinity	$Sal_a =$	33.00	ppt
ambient density	$\rho_a =$	1023.02	kg/m ³
ambient kin. viscosity	$\nu_a =$	1.05E-06	m ² /s

- drinking water (permeate)

flowrate	$Q_{drink} =$	5.00	m ³ /s
recovery rate	$r_{dist} =$	33	%
distillation intake flowrate	$Q_{in} =$	15.15	m ³ /s

- brine characteristics (effluent from desalination process)

brine flowrate	$Q_{brine} =$	10.15	m ³ /s
temperature	$T_{brine} =$	90.00	°C
salinity	$Sal_{brine} =$	49.25	ppt
density	$\rho_{brine} =$	1001.58	kg/m ³
substance concentration 1	$c_{brine1} =$	20.00	ppm
substance concentration 2	$c_{brine2} =$	25.00	ppm
substance concentration 3	$c_{brine3} =$	30.00	ppm

- blended effluent 1 - internal - (i.e. cooling water)

flowrate	$Q_{int} =$	35.35	m ³ /s
temperature	$T_{int} =$	20.00	°C
salinity	$Sal_{int} =$	33.00	ppt
density	$\rho_{int} =$	1023.02	kg/m ³
substance concentration 1	$c_{int1} =$	0.00	ppm
substance concentration 2	$c_{int2} =$	0.00	ppm
substance concentration 3	$c_{int3} =$	0.00	ppm

- blended effluent 2 - external - (e.g. waste water or others)

flowrate	$Q_{ex} =$	0.00	m ³ /s
temperature	$T_{ex} =$	20.00	°C
salinity	$Sal_{ex} =$	0.00	ppt
density	$\rho_{ex} =$	998.40	kg/m ³
substance concentration 1	$c_{ex1} =$	0.00	ppm
substance concentration 2	$c_{ex2} =$	0.00	ppm
substance concentration 3	$c_{ex3} =$	0.00	ppm

Plant characteristics:

feedwater flowrate	$Q_{feed} =$	50.51	m ³ /s
rejected effluent flowrate	$Q_{plant} =$	45.51	m ³ /s
recovery rate (desal. plant)	$r =$	9.9	%
effluent temperature	$T_{plant} =$	35.62	°C
temp. difference to ambient	$\Delta T =$	15.62	°C

Final effluent characteristics:

flowrate	$Q_o =$	45.51	m ³ /s
effluent temperature	$T_o =$	35.62	°C
effluent salinity	$Sal_o =$	36.63	ppt
effluent density	$\rho_o =$	1020.57	kg/m ³
buoyant acceleration	$g_o' =$	0.02351	m/s ²
kin. viscosity	$\nu_o =$	7.56E-07	m ² /s
substance concentration 1	$c_{o,1} =$	4.46	ppm
substance concentration 2	$c_{o,2} =$	5.58	ppm
substance concentration 3	$c_{o,3} =$	6.69	ppm

annotations:

$T = 10$ to 180°C (see density calculator)

$Sal = 0$ to 160 ppt (ppt = g/kg)

allowed ranges for viscosity calculation:

$Sal = 0$ to 130 ppt, $T = 10$ to 180°C (El-Dessouky, Ettouney (2002))

recovery rate:

percentage of distillation feedwater converted into distillate;

without cooling water, only for distillation!

following Lattemann (2006): $r_{dist} = 30$ -35 %

$T = 10$ to 180°C (following Lattemann: 90 - 115°C)

with $Sal_{drink} = 0$ ppt (following Lattemann: up to 50 ppt)

e.g. chlorine

e.g. anti-scalants

...

2 to 3 times the intake water flowrate

ambient temperature (allowed range: $T = 10$ - 180°C)

ambient salinity (allowed range: $Sal = 0$ to 160 ppt)

e.g. chlorine (same substance as c_{brine1})

e.g. anti-scalants (same substance as c_{brine2})

... (same substance as c_{brine3})

$T = 10$ to 180°C

$Sal = 0$ to 160 ppt

e.g. chlorine (same substance as c_{brine1})

e.g. anti-scalants (same substance as c_{brine2})

... (same substance as c_{brine3})

intake water for distillation & cooling

following Lattemann (2006): $r = 10$ -13 %

following Lattemann (2006): 5 - 15°C above ambient

mean average

mean average

$g_o' = g \cdot (|\rho_a - \rho_o|) / \rho_a$

$g_o' > 0$: positively buoyant, $g_o' < 0$: negatively buoyant

Figure 8: First table of the MSF-discharge-calculator to compute the final effluent characteristics

5.2 Length scale analysis and flow classification

Characteristical discharge parameters are computed in the second table of the discharge calculators to analyze and interpret a specific discharge condition. Furthermore, the RO-calculator already includes design considerations regarding the discharge geometry and allows to compute a first set of design alternatives. The procedure is hereby based on Jirka (2008).

The computation of characteristical discharge parameters does hereby not aim for computing dilutions or concentration profile distributions, but to distinguish between different flow regimes, namely a flow classification. The so-called length scale analysis allows to distinguishing for example between dominating jet flow regions, thus classifying the flow, as illustrated in Figure 9, where a jet discharges through the cross-sectional area A_o with a steady top-hat velocity profile U_o resulting in the following initial fluxes:

The initial volume flux

$$Q_o = U_o A_o$$

The initial mass flux

$$Q_{co} = U_o C_o A_o$$

The jet is forced by two dominant dynamic quantities, the initial momentum flux

$$M_o = U_o^2 A_o$$

and the initial buoyancy flux

$$J_o = U_o g_o' A_o$$

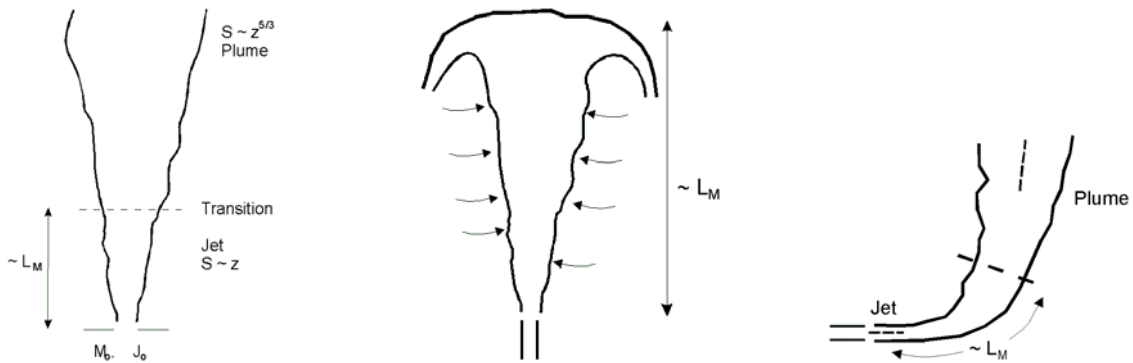


Figure 9: Jet to plume transition length scale L_M for a single jet allows distinguishing between a jet like or plume like single jet behavior (reproduced from Jirka et al, 1996)

A consistent length scale based categorization of the different jet regimes in the presence of crossflow and/or stratification is summarized in Fischer et al. (1979) and modified for plane jets by Jirka and Akar (1991) resulting in the following length scales:

Jet/plume transition length scale:

the distance at which transition from jet to plume takes place (compare with Figure 9)

$$L_M = \frac{M_o^{3/4}}{J_o^{1/2}}$$

Jet-to-crossflow length scale:

the distance beyond which the jet is strongly deflected by the crossflow

$$L_m = \frac{M_o^{1/2}}{u_a}$$

Plume-to-crossflow length scale:

the distance beyond which the plume is strongly deflected by the crossflow

$$L_b = \frac{J_o}{u_a^3}$$

The calculator computes the initial mass fluxes M_o , and J_o , as well as the length scale L_M for further analysis of the jet behaviour. For example a resulting $L_M = 20\text{m}$ indicates that the jet-like behavior will dominate in a region of the order of 20m before density induced motions will dominate further mixing. A screenshot of the second table of the calculators is given in Figure 10 and Figure 11.

Discharge Characteristics RO

- ambient characteristics

ambient density	$\rho_a =$	1023.02	kg/m ³
buoyant acceleration	$g'_o =$	-0.04804	m/s ²
offshore slope	$\theta_B =$	10	°

- effluent characteristics

flowrate	$Q_o =$	11.00	m ³ /s
discharge density	$\rho_o =$	1028.03	kg/m ³
kin. viscosity	$\nu_o =$	1.06E-06	m ² /s

- discharge characteristics

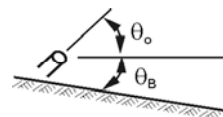
Choose a discharge angle (recommended: 45°) :

discharge angle	$\theta_o =$	45	°
discharge angle as recommended!			
port discharge velocity	$U_o =$	5.00	m/s
number of openings	$n =$	3	
port diameter	$D =$	0.97	m

dens. Froude Number	$Fr_o =$	23.21	
Reynolds Number	$Re_o =$	4.58E+06	

annotations:

$[0^\circ \leq \theta_B \leq 30^\circ]$ only integer!



$[0^\circ \leq \theta_o \leq 90^\circ]$ only integer!

recommended: $U_o = 4\text{--}6\text{ m/s}$

start with one opening!

$$Fr_o = U_o / (g'_o * D)^{1/2} = Q_o / (D^2 \pi / 4) / (g'_o * D)^{1/2}$$

$$Re_o = U_o * D / \nu_o$$

Checking of characteristic properties:

Diameter D : in required range, ok!

Froude Number Fr_o : in recommended range, perfect!

Reynolds Number Re_o : in required range, ok!

required:

$0.1 \leq D \leq 1.0$

$Fr_o \geq 10$, recommended: $Fr_o = 20\text{--}25$

$Re_o > 4000$

Choose an appropriate port diameter (DN according to ISO standard):

port diameter	$D =$	1.00	m
---------------	-------	------	---

Final discharge characteristics:

port diameter	$D =$	1.00	m
number of openings	$n =$	3	
discharge angle	$\theta_o =$	45	°
flowrate (individual)	$Q_{o,ind.} =$	3.67	m ³ /s
port discharge velocity	$U_o =$	4.67	m/s
dens. Froude Number	$Fr_o =$	21.30	
Reynolds Number	$Re_o =$	4.42E+06	
buoyancy flux	$J_o =$	-0.176	m ⁴ /s ³
momentum flux	$M_o =$	17.12	m ⁴ /s ²
discharge length scale	$L_Q =$	0.89	m
momentum length scale	$L_M =$	20.05	m

$$J_o = g'_o * Q_o \text{ (<0: negatively buoyant)}$$

$$M_o = U_o * Q_o$$

$$L_Q = (D^2 * \pi / 4)^{1/2} = Q_o / M_o^{1/2}$$

$$L_M = M_o^{3/4} / J_o^{1/2}$$

Figure 10: Table 2 of the RO-discharge-calculator to compute characteristic discharge parameters

Discharge Characteristics MSF

- ambient characteristics

ambient density $\rho_a = 1023.02 \text{ kg/m}^3$
 buoyant acceleration $g'_o = 0.02351 \text{ m/s}^2$

- effluent characteristics

flowrate $Q_o = 45.51 \text{ m}^3/\text{s}$
 discharge density $\rho_o = 1020.57 \text{ kg/m}^3$
 kin. viscosity $\nu_o = 7.56\text{E-}07 \text{ m}^2/\text{s}$

- discharge characteristics

port discharge velocity $U_o = 5.00 \text{ m/s}$
 number of openings $n = 10$
 port diameter $D = 1.08 \text{ m}$

dens. Froude Number $Fr_o = 31.43$
 Reynolds Number $Re_o = 7.12\text{E+}06$

annotations:

recommended: $U_o = 4\text{--}6 \text{ m/s}$
 start with one opening!

$$Fr_o = U_o / (|g'_o| * D)^{1/2} = Q_o / (D^2 \pi / 4) / (|g'_o| * D)^{1/2}$$

$$Re_o = U_o * D / \nu_o$$

Checking of characteristic properties:

Diameter D : **out of range, please add openings!**

Froude Number Fr_o : **in required range, ok!**

Reynolds Number Re_o : **in required range, ok!**

required:

$0.1 \leq D \leq 1.0$

$Fr_o \geq 10$, recommended: $Fr_o = 20\text{--}25$

$Re_o > 4000$

Choose an appropriate port diameter (DN according to ISO standard):

port diameter $D = 1.10 \text{ m}$

Final discharge characteristics:

port diameter $D = 1.10 \text{ m}$
 number of openings $n = 10$
 flowrate (individual) $Q_{o,ind.} = 4.55 \text{ m}^3/\text{s}$
 port discharge velocity $U_o = 4.79 \text{ m/s}$
 dens. Froude Number $Fr_o = 29.78$
 Reynolds Number $Re_o = 6.96\text{E+}06$
 buoyancy flux $J_o = 0.107 \text{ m}^4/\text{s}^3$
 momentum flux $M_o = 21.79 \text{ m}^4/\text{s}^2$
 discharge length scale $L_Q = 0.97 \text{ m}$
 momentum length scale $L_M = 30.83 \text{ m}$

$$J_o = g'_o * Q_o \quad (> 0: \text{positively buoyant})$$

$$M_o = U_o * Q_o$$

$$L_Q = (D^2 * \pi / 4)^{1/2} = Q_o / M_o^{1/2}$$

$$L_M = M_o^{3/4} / J_o^{1/2}$$

Figure 11: Table 2 of the MSF-discharge-calculator to compute characteristic discharge parameters

The discharge-calculators require the definition of an average offshore bed slope (only for RO), a discharge angle for the submerged discharge pipe(s) and the number of openings. For both usually the user should start with one port and increasing the number to achieve required characteristics. The calculator automatically computes the port diameter of the discharge pipe, assuming an energetic discharge (with exit velocities of $U_o = 4\text{--}6 \text{ m/s}$). It furthermore computes the densimetric Froude number

$$Fr_o = U_o / \sqrt{|g'_o| D}$$

and the Reynolds number

$$Re = \frac{U_o D}{\nu}$$

both measures to characterize the mixing characteristics of the discharging jet, where high Froude and Reynolds numbers indicate good mixing conditions. The calculator includes recommendations for typical design values ($F_o > 10$, $Re \gg 4000$), thus allows to easily find proper configurations and fast analysis.

A complete flow classification system based on the above length scale definitions has been established by Jirka and Akar (1991) and Jirka and Doneker (1991). This classification system alone allows to define resulting flow classes without even starting a numerical computation. The near-field mixing model CORMIX (www.cormix.info) is, in fact, a collection of several models for several sub-processes. These models are invoked through a length-scale based classification scheme that first predicts the discharge flow behavior (so-called flow classes) and then consecutively links (couples) the appropriate zone models (so-called modules) to provide a near-field prediction.

5.3 Nomograms and screening equations (RO)

Another advantage of characteristic length scale analysis is the normalization of different configurations and conditions, which is the base for nomograms. Whereas velocities and concentrations can successfully be normalized by their initial values, results for example for measured trajectories historically normalized by the individual jet diameter showed large scatter, for example for single buoyant jets in the left diagram of Figure 12. Numerous different solutions have hereby been obtained for different initial densimetric Froude numbers. The parameter combination based on the flux definitions instead resulted in the correct scaling (Figure 12, right) using the momentum length scale $L_M = M_o^{3/4}/J_o^{1/2}$ (Jirka, 2004). Such diagrams can be used to predict and estimate for example the trajectory location.

The RO-discharge-calculator already includes first results for such nomograms. The procedure is hereby based on Jirka (2008). For simplicity the most conservative case of stagnant ambient flow (no ambient velocity) is considered herefore. Figure 13 defines general parameters in a schematic side view of a negatively buoyant jet discharging into a receiving water body with a local ambient water depth H_{ao} and a sloping bottom with inclination angle θ_B . The port geometry is given by its diameter D , its height above bottom h_o , and its inclination angle θ_o above the horizontal, pointing offshore. The receiving water is unstratified with a constant density ρ_a and stagnant. The jet has a discharge velocity U_o and density $\rho_o > \rho_a$. The turbulent jet that results from this high velocity discharge first rises to a maximum level and then falls downward under the influence of the negative buoyancy until it impinges on the sloping bottom. Impingement is a complex three-dimensional process, with forward, lateral, and partially reverse spreading, until a density current is formed that propagates downslope.

The procedure from Jirka (2008) has been coded into the RO-discharge-calculator spreadsheet to allow for fast screening calculations (Figure 15). It only requires the definition of the port height ($h_o = 0\text{m}$ or between 0.5 to 1.0m) in the third table. The calculator automatically computes the jet centerline position at the maximum level of rise (x_{max} , z_{max}) and at the impingement point which is used to determine the outfall location (required water depth and distance from shoreline). Furthermore, the minimum centerline dilution at z_{max} , the bulk dilution at impingement point and the substance concentrations at these two points are calculated.

Note that the calculation of the imaginary offshore slope and the consideration of the port height for the calculation of the new x_i position is not (yet) implemented. A higher port position causes slightly higher z_i values if bottom slope $> 0^\circ$ and increasing x_i values for decreasing slopes θ_B and decreasing discharge angles θ_o as shown in Figure 14. For first estimates this displacement is negligible, it does not significantly influence the plume behavior and properties.

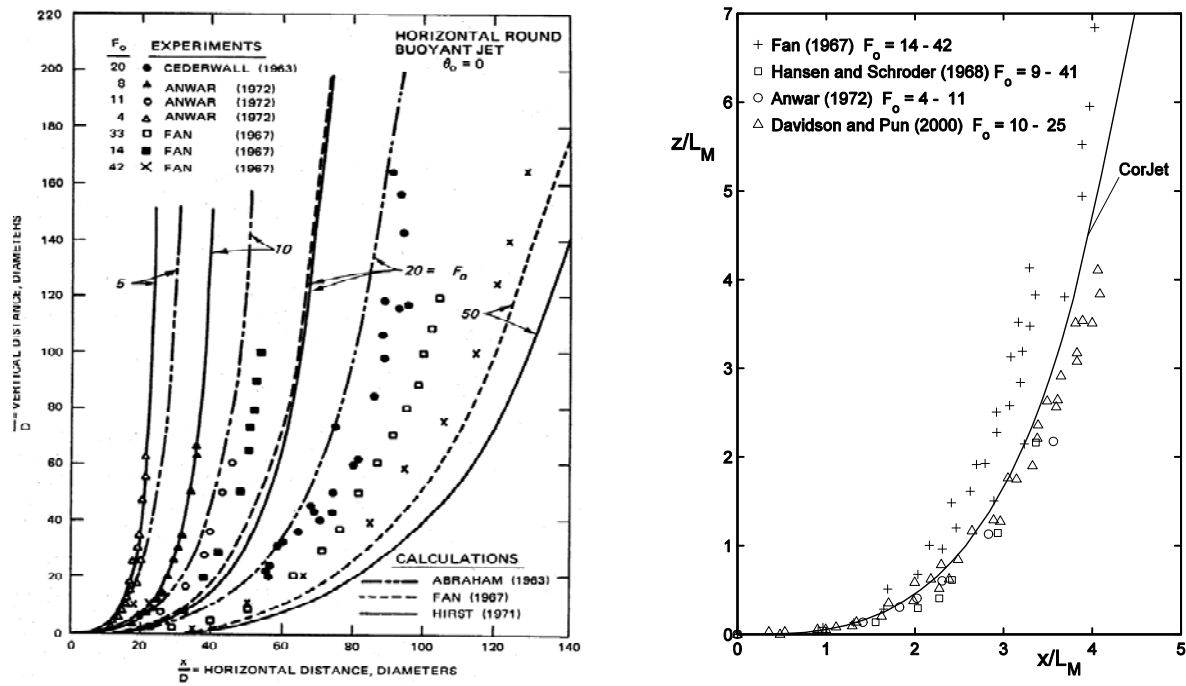


Figure 12: 3-dimensional horizontal buoyant jet trajectories for a single port discharge in stagnant ambient. Comparison between predictions and experimental data. *Left:* normalized with port diameter. *Right:* normalized with momentum length scale L_M (reproduced from Jirka, 2004)

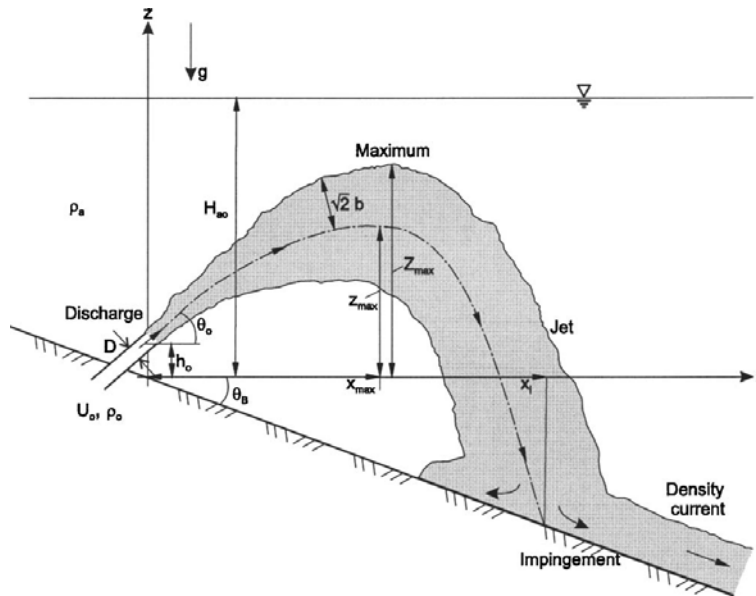


Figure 13: Schematic side view of negatively buoyant jet discharging into stagnant ambient with sloping bottom (Jirka, 2008)

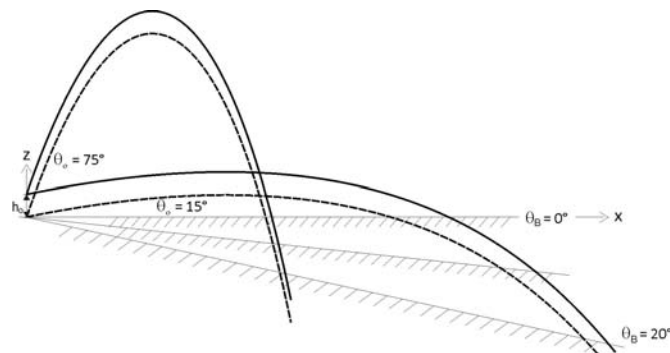


Figure 14: Displacement of impingement point due to increasing port height

However, the above procedure and illustrations apply to a discharge into stationary, non-flowing ambient conditions that are typically the most limiting for dilution. Detailed application of mixing models is needed for cases of flowing environment, leading to more complex three-dimensional trajectories. Furthermore, in case of large volume discharges it may be necessary to distribute the flow over several ports, i.e. a multiport diffuser, a situation that can also be predicted by models. The CorJet model (as used in Jirka, 2008) can be used embedded within the CORMIX expert system (Jirka et al., 1996) that allows for the prediction of not only the buoyant jet phase, but also of other mixing processes, such as the formation of the bottom density currents, boundary interactions, and transitions to far-field mixing. A special version DCORMIX for brine discharges from desalination plants (Del Bene et al., 1994), or for sediment currents (Doneker et al., 2004), that includes the dynamics of the downward propagating density current can be used for a complete environmental impact evaluation.

Jet Properties RO

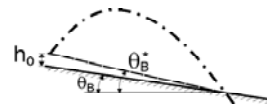
- discharge & ambient characteristics

discharge angle	$\theta_o =$	45 °
port height	$h_o =$	0.00 m
port at seabed		
offshore slope	$\theta_B =$	10 °
imaginary offshore slope	$\theta_B^* =$	10 °
momentum length scale	$L_M =$	20.05 m
dens. Froude Number	$Fr_o =$	21.30

annotations:

$h_o = 0\text{m}$ or $h_o = 0.5\text{-}1.0\text{m}$

due to port height, not yet implemented



- geometric jet properties (for discharge angles that are not a multiple of 15°: linear interpolation!)

	Z_{max}/L_M (3%)	1.576	(taken from Fig. 2(a))	$(c/c_{max} = 3\%)$
	Z_{max}/L_M (25%)	1.385		$(c/c_{max} = 25\%)$
	Z_{max}/L_M	1.057		
	x_{max}/L_M	1.606	(taken from Fig. 4(a))	!port height not considered!
	z_i/L_M	-0.536		
	x_i/L_M	3.038		
upper jet boundary	Z_{max} (3%)	31.61 m		
	Z_{max} (25%)	27.78 m		
maximum jet centerline position	z_{max}	21.19 m		
	x_{max}	32.20 m		
jet centerline position at the impingement point	z_i	-10.74 m		
	x_i	60.91 m		
offshore location	$x \geq$	1178.07 m		
local water depth	$H_{ao} \geq$	20.83 m		$H_{ao} \geq 0.75Z_{max}$ (25%)

Choose an appropriate outfall location:

offshore location	$x =$	1180.0 m
local water depth	$H_{ao} =$	20.87 m

in required range,
offshore location ok!

- dilutions & concentration (for bottom slopes that are not a multiple of 10°: linear interpolation!)

minimum centerline dilution at z_{max}	$S_m/Fr_o =$	0.29	Fig. 2(b)
	$S_m =$	6.1	
bulk dilution at impingement point	$S_i/Fr_o =$	1.42	Fig. 4(b)
	$S_i =$	30.3	
substance concentration at the centerline of			
max. level of rise (z_{max})	$c_m =$	1.79 ppm	$S = c_o/c_c \rightarrow c_c = c_o/S$
impingement point (z_i)	$c_i =$	0.36 ppm	

Figure 15: Table 3 of the RO-discharge-calculator to analyze jet discharge characteristics and dilution values

1.1.1. Empirical dilution equations (MSF)

The previous analysis of jet trajectories for RO discharges has still not been done for thermal discharges. This mainly because of the complexities of plant complexes of thermal desalination plants and blended cooling water effluents, but also due to much larger flowrates, which considerably influence the coastal hydrodynamics in the near-field region.

Therefore only a few principles and scaling methods are described for MSF discharges as follows. However, these are only valid for positively buoyant discharges! Major contributions are from Brooks (1960, 1965, 1980, 1984, 1988), and by Koh (1988). Comprehensive reviews are given in Fischer et al. (1979), Wood et al. (1983) and Jirka and Lee (1994). Detailed discussion on buoyant jets were presented by Jirka (1979, 1994), Roberts (1980, 1986) Roberts et al. (1989a,b,c), Lee and Jirka (1981) and Lee and Neville Jones (1987). The resulting equations are all based on the near-field assumption and trying to calculate the minimum jet centerline dilution $S_c = c_o/c_c$ at the end of the near-field, i.e. after surface contact or at the terminal layer for trapped plumes.

One of the key equations is the equation for a line plume in a stagnant unstratified ocean (Rouse et al., 1952):

$$S_c = 0.38 \frac{j_o^{1/3} H}{q_o}$$

For a given flow Q_o , the unit discharge q_o and unit buoyancy flux j are inversely proportional to the diffuser length L_D , and the above equation suggests that a higher dilution is obtained by increasing the length of the diffuser. For a line plume, the minimum dilution can be multiplied by a factor of $2^{1/2}$ to give the average dilution.

It has been demonstrated both theoretically and experimentally (Fischer et al., 1979) that maximum mixing can be achieved with closely spaced ports that allow some interference of adjacent jets. In relatively shallow coastal waters of typical depth 5 – 15 m, however, it is often the case that, given practical considerations (e.g. in order to maintain a minimum jet velocity and minimum diameter), multiport diffusers are designed to minimize interference of adjacent plumes. In such cases, the required spacing is about $H/3$.

In case of a linearly stratified ambient with a density gradient dp_a/dz the maximum height of rise z_{max} to the terminal level and corresponding dilution S_c are given by

$$z_{max} = 2.84 j_o^{1/3} \left(-\frac{g dp_a}{\rho_a dz} \right)^{-1/2} = 2.84 \ell_b'$$
$$S_c = 0.31 \frac{j_o^{1/3} z_{max}}{q_o}$$

In a linearly stratified ambient, the spreading layer is found to occupy about 40 – 50% of the rise height. For computing bulk dilutions, one must allow for the thickness of the wastewater field. Simple models to account for blocking in the presence of an ambient current can be found in Fischer et al. (1979).

Roberts (1979, 1980) studied the mixing of a line source of buoyancy in an ambient current, and found that the shape of the flow field and the dilution are determined by the ambient Froude number $F = u_a^3/j_o$. F measures the ratio of the ambient current velocity to the buoyancy-induced velocity. For $F < 0.1$, the minimum surface dilution S_m is little affected by the current and is given by:

$$S_m = 0.27 \frac{j_o^{1/3} H}{q_o}$$

The smaller dilution coefficient reflects the effect of blocking of the surface layer. For higher crossflow, $F > 0.1$, however, the entrainment is dominated by the crossflow, and the alignment angle γ between the diffuser line and the current direction is important. Higher dilution results for a perpendicular alignment, $\gamma = 90^\circ$, in which the maximum amount of flow is intercepted while the parallel alignment, $\gamma = 0^\circ$, gives the lowest dilution. For $F \approx 100$, the perpendicular alignment results in a dilution

$$S_m = 0.6 \frac{u_a H}{q_o}$$

that is proportional to volumetric mixing between ambient (velocity u_a) and discharge flow, but with a reduced coefficient 0.6. For parallel alignment, the dilution is lower by a factor of about four. Experiments by Mendez-Diaz and Jirka (1996) have examined the different plume trajectories for various crossflow strengths.

The simple dilution equations given in the foregoing are useful for initial design screening of alternatives. They are limited to simplified ambient conditions. For final design evaluations and for more general and complex ambient oceanographic conditions models that are more comprehensive must be employed.

6 Conclusions

Screening and order of magnitude estimates for mixing processes resulting from desalination plant effluents are based on very strong generalization and schematization. However, one should not underestimate the value of such investigations during the planning phase and as a starting point for more detailed environmental impact studies and process modelling.

The here described screening calculators are all based on simplified but validated scientific theories. They are coded in Excel spreadsheets and illustrated with nomograms. The spreadsheet includes a density calculator and, in addition, first estimators for the initial dilution and trajectories of such discharges. Thus, the system will allow to improve the permitting process for desalination brine discharges considerably for both, the dischargers and the regulatory authorities. Furthermore, the analysis allows to improve the plant design and operational conditions by optimizing the siting and design of the intake in relation to the outfall.

The calculators are fast and efficient, but only present the first step of a discharge assessment. Further model applications have to be considered, once the draft configuration has been decided on.

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