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Abstract

Weyland AS plans to establish a biofuels factory in Sørsalten, North Norway. The product will be bio-ethanol from wood-based material/cellulose. The factory is planned to be located at the head of Foldfjorden. Biofuel production would lead to discharge of sulphate, either as solid, inert calcium sulphate (“gypsum”), or as liquid sodium sulphate. Both substances are common in seawater, and as such they do not constitute anything new or harmful. The report evaluates the likely dispersion or disposal of the future discharge. The liquid is heavy and will tend to flow in a layer about 12 m above the sea bottom, dispersed by the ambient currents. The solid waste will remain in place on the seabed at the disposal site. Both types of discharge will impact to some extent the water chemistry and local biota near/at the discharge point, inside the mixing zone. Assuming that the waste holds no significant amounts of toxic substances, the environmental impacts are projected to be small.

4 keywords, Norwegian	4 keywords, English
1. Natriumsulfat	1. Sodium sulphate
2. Kalsiumsulfat	2. Calcium sulphate
3. Sørfold kommune	3. Sørfold municipality
4. Foldfjorden	4. Foldfjord



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Sodium and calcium sulphate release into a marine recipient

A theoretical assessment of fate and effects

Preface

The company Weyland AS in Bergen, Norway, has developed a new industrial process to convert lignocellulose plant material into bio-ethanol. A pilot plant is established in Bergen and a large-scale plant is planned to be located in Sørfold, Salten district in Nordland County. The industrial process will imply some discharges to the fjord nearby.

Due to these discharges, NIVA, the Norwegian Institute for Water Research, was contracted by Weyland to make a preliminary and theoretical assessment of possible marine environmental impacts from these. The accompanying work was of a desk-top study type, with literature study and some theoretical computations based on given scenarios. No field investigations or measurements were undertaken during the project period.

Several local persons contributed with information about Foldfjorden in particular: Erik Stendal and Margrete Myran of Sørfold municipality, Pål Arve Dypaune of Sisomar AS, Alf Brandsæter, Runar Olsen and John Kr. Magnussen at Elkem Salten AS

Eivin Stand at the Institute of Marine Research in Bergen provided some oceanographic data.

Jørn Einen was the contract representative at Weyland.

Bergen/Oslo, December 2011

Lars G. Golmen

Contents

1. Summary	5
2. Background and introduction	6
2.1 The Weyland process	7
2.2 Discharge to the sea	9
2.2.1 Effects of temperature	10
2.2.2 Solid material disposal	12
3. The Foldafjord/Sørfolda, short description	13
3.1 Previous studies of the fjord area	13
3.2 Description of the alternative discharge components	15
3.2.1 Sodium sulphate	15
3.2.2 Calcium sulphate	17
4. Seawater chemistry	18
5. Dispersion calculations	21
5.1 Cormix	21
5.2 Discussion	26
5.2.1 Chemical reactions in the fjord water	26
5.3 Recommended follow-up	27
6. References	28
7. Appendix	29

1. Summary

The Norwegian Institute for Water Research, NIVA, was awarded a project from Weyland AS in 2010 to assess the possible fate and effects of certain marine discharges from a proposed biofuels factory in Sørsalten, North Norway. The factory will produce bio-ethanol from wood-based material/cellulose in a process developed and patented by Weyland AS. The material can be waste material from lumbering, saw mills and wood ware factories.

The factory will be established back-to-back with the existing Elkem Salten (Salten verk) metallurgy plant at the head of Foldfjorden, utilizing some of their waste heat flow. The discharges in question will be sulphate, either as calcium sulphate, or as sodium sulphate. Both substances are common in seawater, and as such they do not constitute anything new or harmful. However, due to the comparatively large quantities and concentrations, some local influence cannot be ruled out and this is the concern and subject for the present evaluation.

No field sampling or local investigations on land or in the sea area under consideration were conducted during the project. The present assessments are thus truly theoretical, based on some very limited existing data on the local marine environment and then setting up certain scenarios for dispersion etc. based on this, for the liquid effluent case.

A total volume flux, water + solute of ca 50 m³/h is anticipated. A discharge at 30 m depth will interleave somewhere between 2 m and 11-12 m above the bottom (at about 18 m water depth). At this dilution stage, the dilution factor will be about 60-70, i.e. 1 unit volume of discharge mixed with 60-70 volumes of ambient (fjord) water. A winter situation with weaker stratification in the fjord than we have anticipated, will probably give somewhat shallower interleaving. Dilution will rapidly increase further away from the discharge location.

A submerged discharge at 30 m depth from the Weyland plant for the liquid discharge of sodium sulphate with the stated flux of ca 50 m³/h totally (solvent + solute) thus seems to give satisfactory dispersion in the marine recipient Sørfolda bay.

A more detailed design of the discharge and refined calculations based on actually measured data from the fjord should be made prior to a final decision on locating the discharge. Then a full ecological pre-assessment should be made.

The discharge area should also undergo an ecological survey as a baseline investigation, before the discharge is established. The same will apply for a site for the alternative disposal of calcium sulphate, this case was only treated in a superficial manner in the present study, referring to analogues of disposal such as that of mine tailings.

2. Background and introduction

The Norwegian institute for water research, NIVA, was awarded a project from Weyland AS in 2010 to assess the possible fate and effects of certain marine discharges from a proposed biofuels factory in Sørsalten, North Norway (**Figure 1**). The factory will produce bio-ethanol from wood based material/cellulose in a process developed and patented by Weyland AS. The material can be waste from such as lumbering, saw mills and wood ware factories.

The factory will be established back-to-back with the existing Elkem Salten (Salten verk) metallurgy plant at the head of Foldfjorden, utilizing some of their waste heat flow. The discharges in question will be sulphate, either as calcium sulphate, or as sodium sulphate. Both substances are common in seawater, and as such they do not constitute anything new or harmful. However, due to the comparatively large quantities and concentrations, some local influence cannot be ruled out and this is the concern and subject for the present evaluation.

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Figure 1. Map of Norway and Sweden, with the approximate location of the new Weyland plant (arrow) in Northern Norway.

2.1 The Weyland process

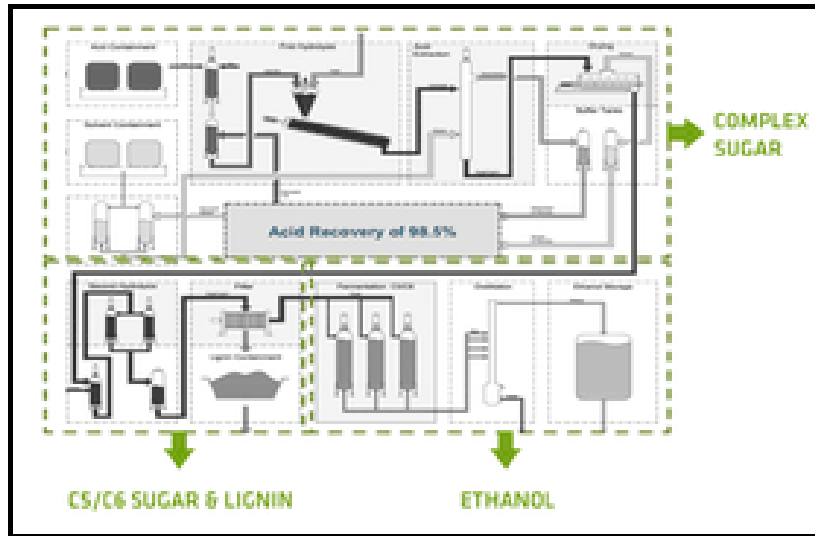
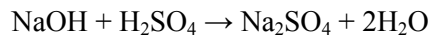


Figure 2. Sketch of the industrial process (from www.weyland.no).

Sulphuric acid is the main strong acid used in the Weyland process to degrade the material. A vital element of the process is reuse of the acid, about 98.5% will be purified and recycled (**Figure 2**).

In the neutralization of the remaining (waste) acidic solution, NaOH may be used. This will cause the formation of large amounts of sodium sulphate, about 10.000 tonnes annually, according to the following reaction:



In order to obtain maximal neutralization, the NaOH will be coexisting and added throughout the whole waste handling process, including the water purification stage. Then, eventually, dissolved sodium sulphate will be discharged to the sea.

The factory may, alternatively, neutralize the acid by adding calcium carbonate, CaCO_3 . This will generate about 10.000 tonnes annually of dry/solid calcium sulphate waste, corresponding to ca. 20.000 tonnes of wet heavy slurry, (or “cake”).

The waste will then either consist of dissolved Na_2SO_4 or (solid/slurry) CaSO_4 .

In order to reduce handling and transport cost (and environmental impact associated with this), it is planned to lead the dissolved constituent Na_2SO_4 via a submerged pipeline to the deeper parts on the inner Foldfjord (Sørfolda). The exact depth and location of the discharge is not yet determined.

If the CaSO_4 will be the end product, this will have either to be stored at a disposal site on land, or to be transported by a vessel and then dropped to the sea bottom in an appropriate location in Foldfjorden or surrounding fjords or coastal area (**Figure 3**).

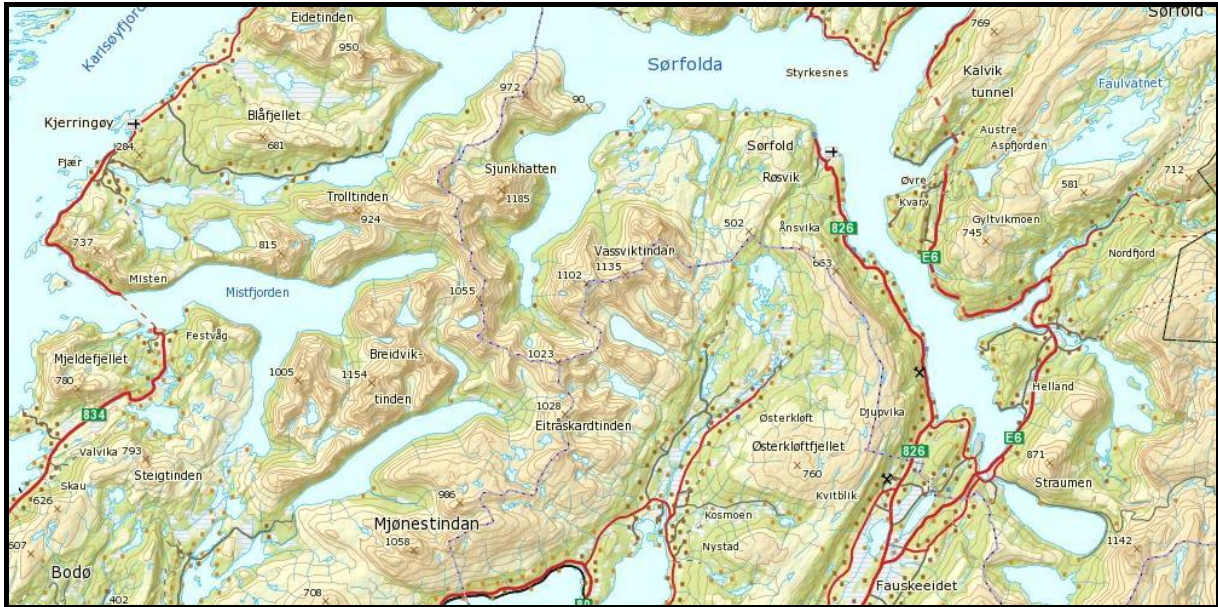


Figure 3. Map over larger Salten district with the Sørfolda fjord (Norw. Nautical Chart No 227.)

NaOH neutralization (Na_2SO_4 discharge) seems to be the best alternative from an industrial process point of view (disregarding any possible negative environmental aspects).

From an environmental impact point of view this would require that the discharge of sodium sulphate will have no or minimal impacts on the marine environment in the fjord area under consideration.

This area may theoretically also include the adjacent Straumsvatn, a deep land-locked, meromictic bay/lake with opening to the Inner Foldfjord.

In principle the same view is valid for the other type of discharge or disposal, CaSO_4 , if that, eventually, will be the selected alternative.

2.2 Discharge to the sea

The liquid discharge via pipeline will be at or close to the sea bottom. Depending on the composition, i.e. density of the discharge, the outflow may either sink towards the bottom, interleave at neutral level in the surrounding seawater, or rise towards or all the way to the surface. Figure 4 depicts the three scenarios.

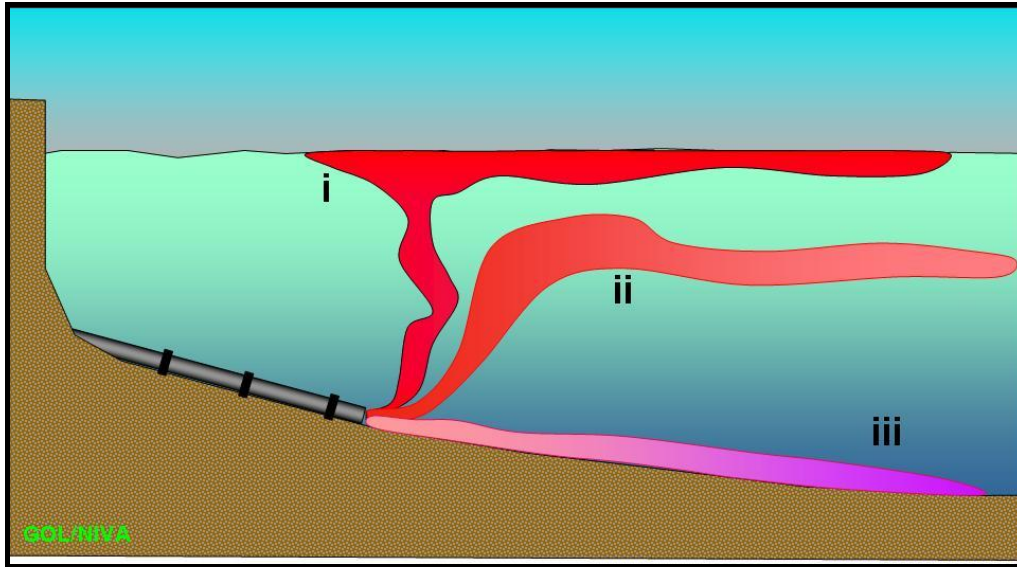


Figure 4. Sketch showing possible scenarios for a submerged discharge. I: Discharge with low density relative to the ambient seawater, rising to the surface; II: medium density discharge, interleaving, and, III: High-density discharge, flowing along the sea bottom.

Table 1. Information about the marine discharge.

Constituent	Flux/hour	Concentration in raw discharge
Fresh water flux:	48.67 tonnes/hour	
Flux of misc. NaSO ₄ salts:	6 kg/hour	0.12 kg/m ³
Flux of Na ₂ SO ₄ :	1.26 ton/hour	25.9 kg/ m ³
Flux of organic residual components:	5 kg/hour	0.1 kg/ m ³

Actual concentrations may be adjusted by mixing with seawater before discharging.

The initial temperature will be ca 35 °C. This may be lowered in a cooling/cycling circuit.

pH of the discharge will be about 6.0.

The mixture as specified, with ca 50 tonnes/hr of water carrying 1.26 tonnes of Na₂SO₄, probably as suspended matter, and only 6 kg of dissolved salts. Disregarding any effects from the elevated temperature, the small amounts of dissolved salts will result in a bulk discharge density of only slightly above 1000 kg/m³, while the ambient seawater probably will be in the range 1022-1025 kg/m³ in deeper strata.

The presence of significant amounts of Na₂SO₄ as particulate matter will theoretically result in a two-phase discharge plume, one phase represented by the light liquid, and the other by the heavier phase with suspended particles. In practice, the particles will add to the bulk density of the plume, so that its

behaviour in the initial dilution stage will probably be somewhere between fresh water and saline seawater. We have assumed that the discharge is light, compared to the ambient seawater. But the suspended matter contributes by increasing the bulk density of the plume. We have assumed bulk densities of 1005 and 1010 kg/m³ in our modelling (see also next para. about temperature effects). For a submerged discharge this would likely be similar to scenario II in the figure above. The density of the discharge may be adjusted by diluting with extra water, possibly seawater, to decrease or increase the density.

2.2.1 Effects of temperature

As the discharge water initially will be quite warm, 35°C, it will imply a significant impact on the density of the discharge solution. Figure 5 illustrates some effects of salinity- and temperature changes to the density of seawater. Warm and less saline water will be lightest. A discharge of 35°C will be on the order of 3 sigma-t units lighter than water of similar salinity, but at ambient temperature (fjord water) of 5-10 °C. This will favour a rising plume, rising in the water column, possibly all the way to the surface (scenario I above).

From an environmental point of view, it is usually preferred (and even required) to have the discharge water interleave in the water column, and not rise to the surface. Reducing the buoyancy (increasing density), if possible, is a way to achieve this, and cooling before discharging represents one method.

As the pipeline will extend probably a few hundred metres along the sea bottom from the shore, some cooling of the flow inside the pipe against the ambient must be expected, before the flow discharges. This may amount to a few degrees. By allowing the discharging water first to circulate in a cooling basin on shore, a larger depression of temperature will be achieved.

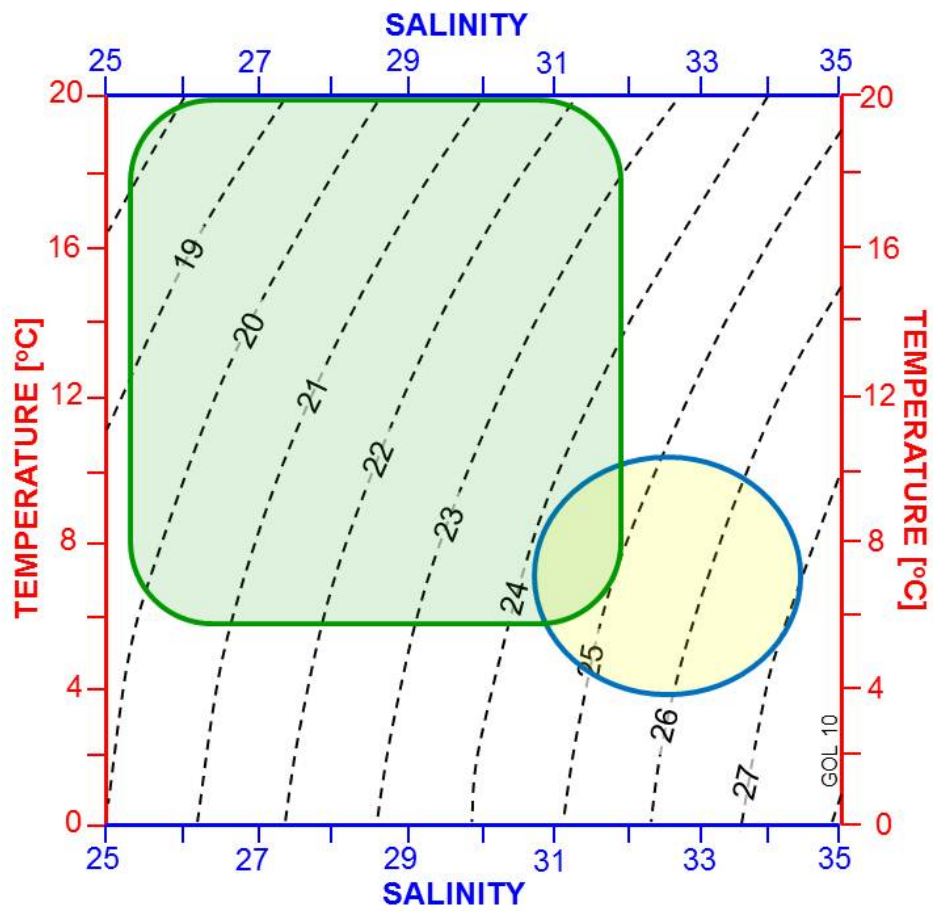


Figure 5. T-S diagram with possible distribution in temperature-salinity space of the ambient water (circle) and the discharge water (square).

2.2.2 Solid material disposal

The disposal of gypsum may be done from a barge or other vessel carrying the waste from the factory in batches. The solid material will rapidly sink to the bottom, sinking at 50-100 cm/s speed probably. A small residual fraction of minute particles will stay suspended in the water and will be carried away by the ambient current.

The material accumulating on the seabed will stay in place within a specified, confined area, provided the site is deep and has low water flow velocity near the bottom. The dissolution and leakage of matter from the material will be diminishingly small, and only the top layer will be exposed to the seawater above.

Bottom living animals (benthic fauna) may after some time inhabit parts of the disposal pile, most likely along the outer borders. Burrowing animals may imply a redistribution of material, re-exposing some to the seawater and burying some. At other disposal sites, e.g. at Hustadmarmor, Elnesvågen (limestone slurry, Schaanning et al., 2009) impacts of the disposed material has been studied more extensively. Impact is evident at the disposal site, where biota is scarce or absent, either from the constantly new material being deposited, or also by toxic effects of the material, that limit recolonization and habitation.

Skei et al. (2010) reviewed the experiences from disposal of mine tailings to sea, which takes place at several locations in Norway. This material is commonly not inert, but has certain amounts of reactive and toxic substances, e.g. in sulphidic tailings. Additionally, they may represent some oxygen demand, depriving the ambient water of oxygen, especially if stagnant.

The comparison of mine tailings disposal with the present disposal of calcium sulphate may thus not be so relevant as what regards chemical/biological impacts. Some lessons may still be learned from it, such as operations, siting and spatial extension of the disposal area etc.

Sea disposal of mine tailings in Norway has not caused and reported impacts on fisheries/marine resources, although the topic is not extensively studied. At the Island Copper Mine in Canada local fishers some 8 km from the disposal site were interviewed about their experiences, with no complaints or allegations after 24 years of operations (Skei et al., 2010).

According to the above, disposal from non-sulphidic mines such as Titania and North Cape Minerals may provide relevant background information and experience for Weyland to prepare for disposal of calcium sulphate.

3. The Foldafjord/Sørfolda, short description

Sørfolda is a fjord belonging to the municipalities of Sørfold and Bodø in Nordland County. The Inner Foldfjord which lies next to the site for the industrial plant, constitutes the southern branch or extension of the main fjord Folda in the district of Salten, which is more than 400 m deep.

The community Straumen lies at the head of inner Foldfjord, this is the administrative centre of the municipality of Sørfold.

See maps, **Figure 6 - Figure 8** for more information.



Figure 6. Map over the inner Sørfolda fjord with Straumen and Salten Verk to the south.

3.1 Previous studies of the fjord area

Straumsvatn connects to the inner Foldfjord through the shallow outlet and may thus be part of the recipient of a future discharge in Foldfjord. Arnesen and Iversen (1975) made some investigations in Straumsvatn. The reason for the investigations were a plan or proposal dispose of industrial waste material (SiO_2 dust) from the Elkem-Spigerverket plant.

Straumsvatn has a maximum depth of 162 m, and the water below ca 120 m is saline, while the upper layers remain fresh of low-saline. This kind of stratification reduces the ventilation of the deeper layer, causing anoxia there and high concentrations of dissolved hydrogen sulphide, H_2S (60 mg/l measured in 1975; this seems to be the only data from the deep parts of this lake). Saline water from the adjacent fjord probably only rarely makes it way through the entrance, this may happen e.g. at occasions of very high tide. Inflowing seawater then sinks towards the bottom due to its higher density, causing some renewal and oxygen supply to the deep water.

The Straumsvatn may have less relevance for the present evaluations, but as it is adjacent to the possible disposal area it should not be totally excluded as a water body that theoretically might become affected from a discharge or disposal in the outside fjord.

Øvreeide (1983) made an investigation on aquaculture (fish farm) sites in Nordland County, including Sørfolda and the site Kines on the west side further out in the fjord, ca 10 km from the Weyland pipeline discharge. That site was described as having water exchange conditions with varying hydrography (salinity, temperature) in the upper layer. The report presents a couple of profiles (graphs) from Kines in 1978 but the print quality makes it difficult to extract exact figures. The report also describes the flow pattern in the Sørfold bay as being “complex” with a low-salinity surface layer above a layer with compensating (inward flowing) current and higher salinity. Salinity increased from south to north in the fjord. The lowest measured seawater temperature in 1978 was 3.8 °C.

Skreslett (1991) refers to investigations of fjords in the Salten district, a bit to the north of our area of interest. The data described, may provide some auxiliary source of information in light of the seeming lack of marine data from the Inner Sørfolda fjord.

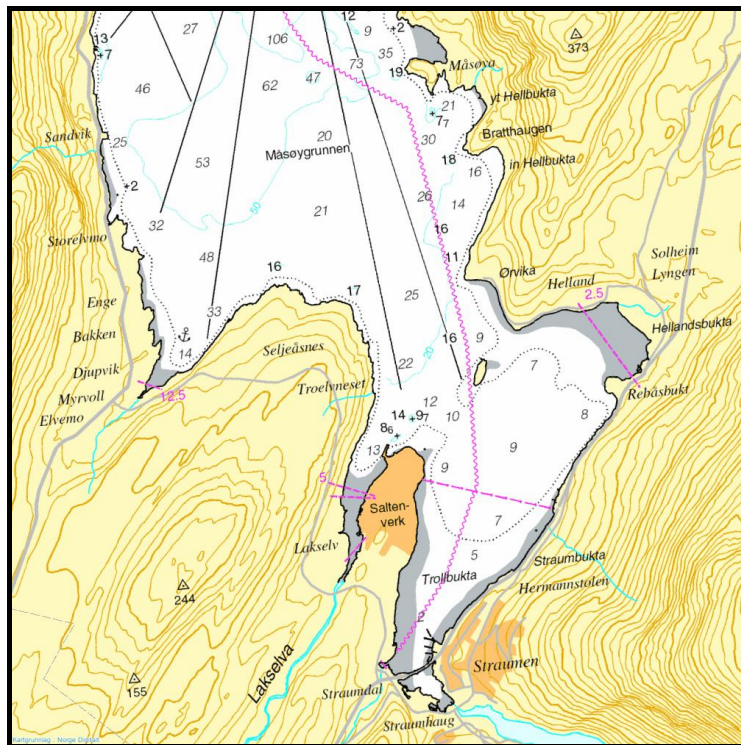


Figure 7. Another map (Gislink) over the Sørfolda fjord with the community Straumen.

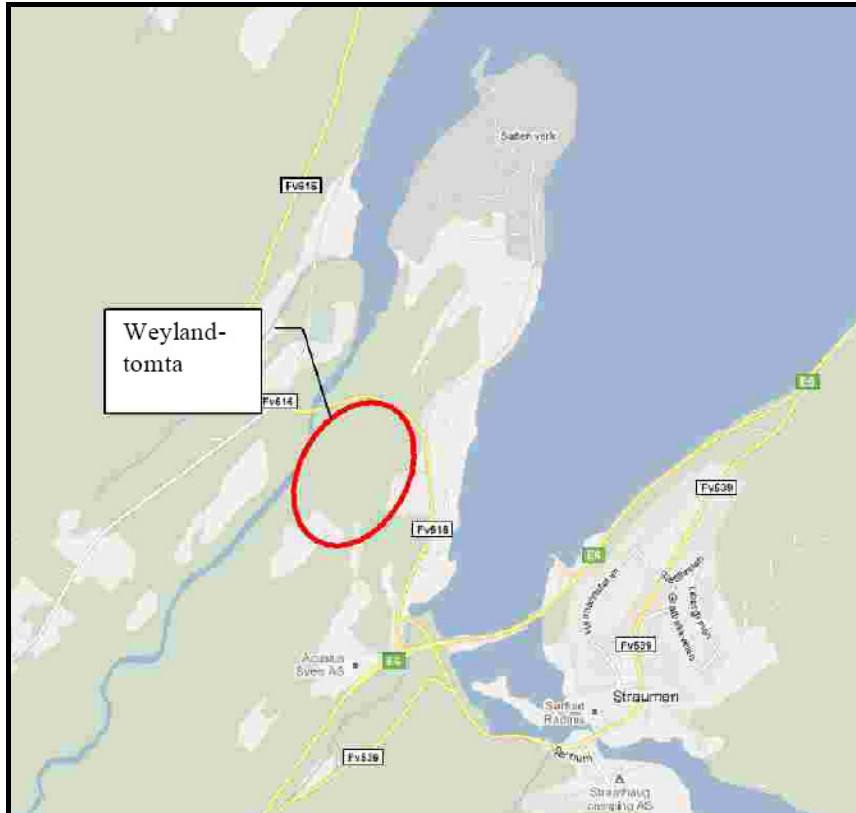


Figure 8. Approximate location of the Weyland site. (Map provided by Sørfold municipality).

3.2 Description of the alternative discharge components

3.2.1 Sodium sulphate

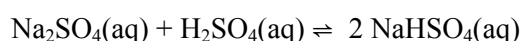
Sodium sulphate is a common substance used in ingredients or products such as detergents, paper, textiles and glass. It is composed of Na^+ and SO_4^{2-} ions.

Sodium sulphate solubility in pure water is 4.8 g/100 g at around 30 °C temperature (**Figure 9**). It is a neutral salt that dissolves in water, leaving the pH unchanged.

The variant decahydrate is used for solar energy production as it melts (absorb heat) of crystallizes (expels heat) according to the varying temperature.

Sodium sulphate is chemically very stable and reacts very little with both oxidizing and reducing agents at normal ambient temperatures. (At very high temperature it may be reduced sodium sulphide).

Sodium sulphate may react with sulphuric acid to form sodium bi-sulphate:



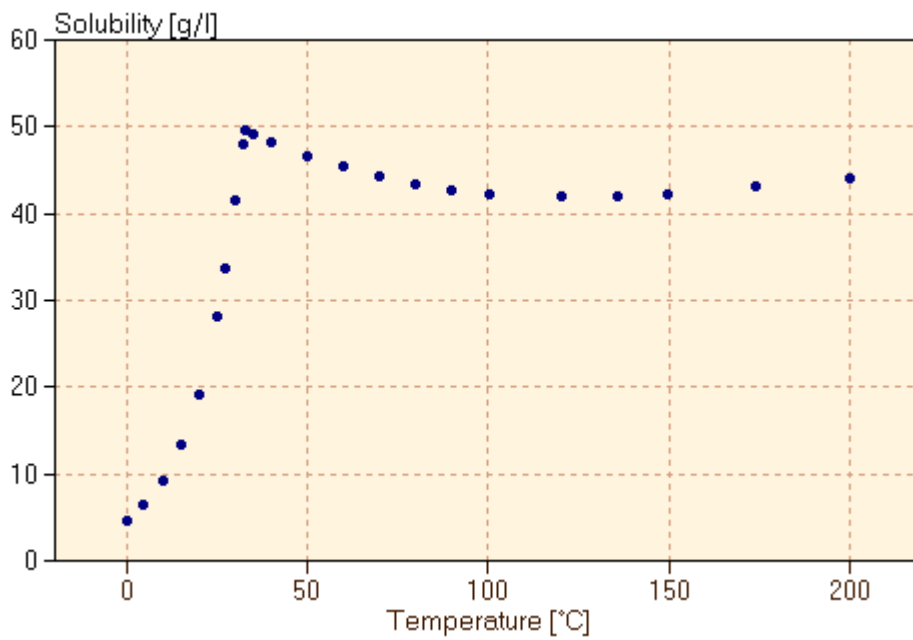


Figure 9. Solubility of sodium sulphate according to temperature.

The solubility in water is highly temperature dependent. It increases by a factor of 10 as temperature rises from 0 to 32.4 °C at the maximum solubility. At this temperature any hydrate salt is melting.

3.2.2 Calcium sulphate

Calcium sulphate (Calcium dihydrate, “gypsum”) is a solid substance, with maximum density of 2.96 kg/l. The solubility in water is, low, 0.2 g/100 g. A solubility curve is shown in **Figure 10**.

Gypsum rock, ($\text{CaSO}_4 \times 2\text{H}_2\text{O}$, calcium sulphate dihydrate) is found commonly on Earth, Seawater contains dissolved calcium sulphate. Gypsum is formed naturally by precipitation from stagnant seawater under slow evaporation.

The substance is commonly used as ingredient in various human food products, where it is named E-516. Products like cakes, dietary products, in deserts as thickening agent and for regulating pH.

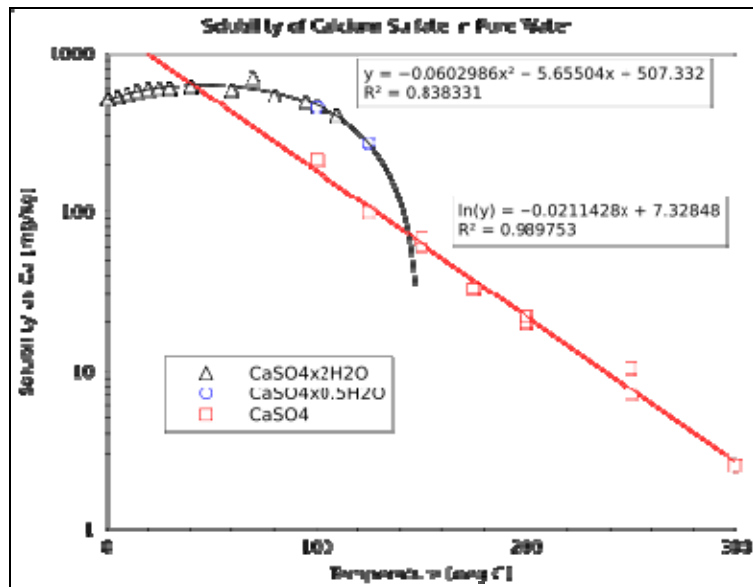
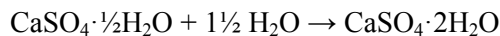


Figure 10. Solubility in water of calcium sulphate as function of temperature.

When calcified gypsum is mixed with water at normal temperatures it is transformed into a dihydrate, forming a solid crystalline structure:



This reaction is exothermic (gives off heat), and is thus thermodynamically favourable.

4. Seawater chemistry

Seawater will act as the solvent in the context of the discharge or disposal of the effluents from the Weyland plant in Sørfolda. Thus it is important to know about the main properties of seawater, especially those from which any reactions or side effects may occur.

The chemistry of seawater is complex as most metals, tracers and salts are dissolved in it. The dominating components are sodium, calcium, magnesium, chlorine and sulphate, see **Figure 11** and **Table 2**.

The carbonic components (such as CO_3^{2-}) constitute only a small part, and actually the normal concentration of Ca^{2+} is about 100 times the concentration of carbonate at normal pH. In the upper layers of the ocean and fjords, there is normally a state of supersaturation of Ca and the concentration of carbonate that determines how much and how fast, calcium carbonate can solidify in shells etc. The bicarbonate concentration drops with decreasing pH (**Figure 12**), an issue that is important in the study of ocean acidification (dropping pH in the ocean).

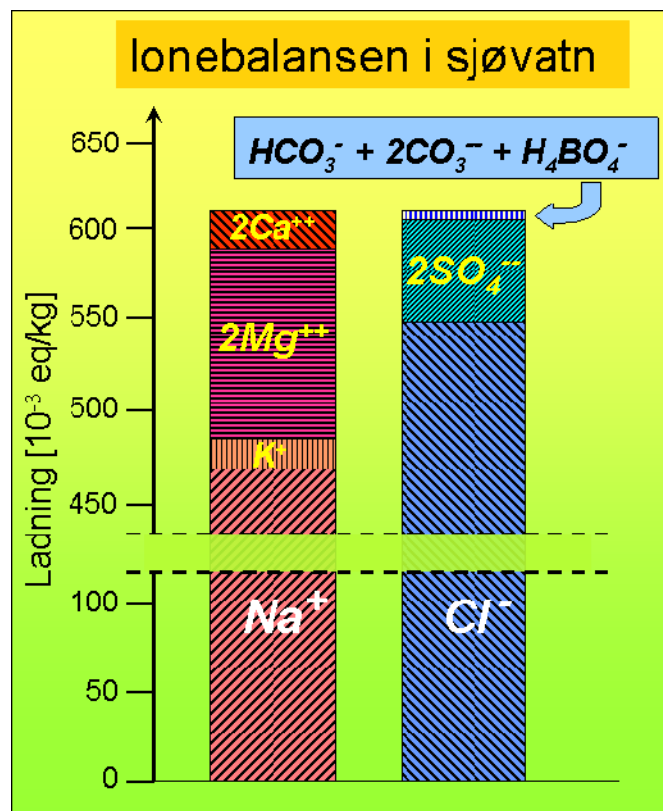


Figure 11. The ionic composition of seawater, for the major components, where Na^+ and Cl^- dominate. Remaining parts contain cations like Mg^{++} , Ca^{++} and K^+ and anions like SO_4^{2-} . The anions bicarbonate, carbonate and borate (= the “alkalinity” of seawater) constitutes only a minor part, by mass. Redrawn from Brooker and Peng (1998).

Figure 13 illustrates the CO₂-balance in the ocean and the pH-dependent equilibria. The Ca-reaction from dissolved to solid and reverse is also illustrated. A bit simplified it may be said that the sum of the forms H⁺, Ca⁺⁺, CO₂, HCO₃²⁻ and CO₃²⁻ are constant in the ocean, and the equilibrium is determined by the three equilibrium constants. A change in the concentration of one form/constituent will have an impact on the remaining concentrations.

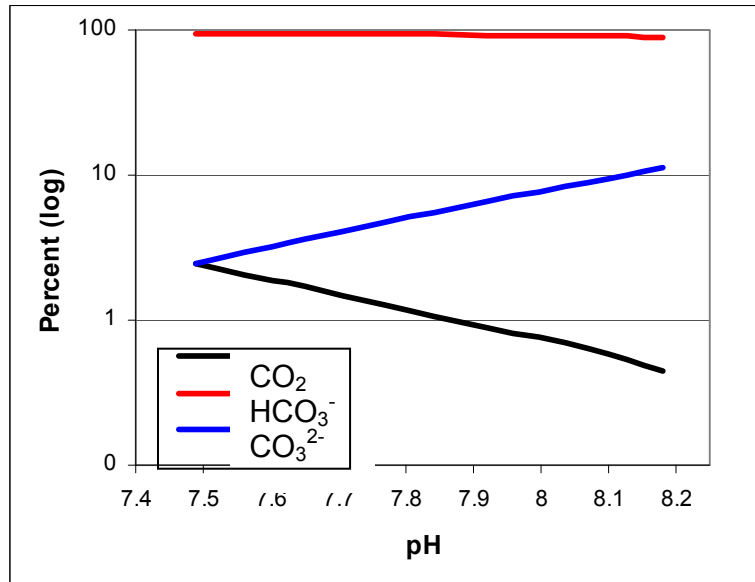


Figure 12. The concentration of carbonate, bicarbonate and free CO₂ in seawater as function of pH.

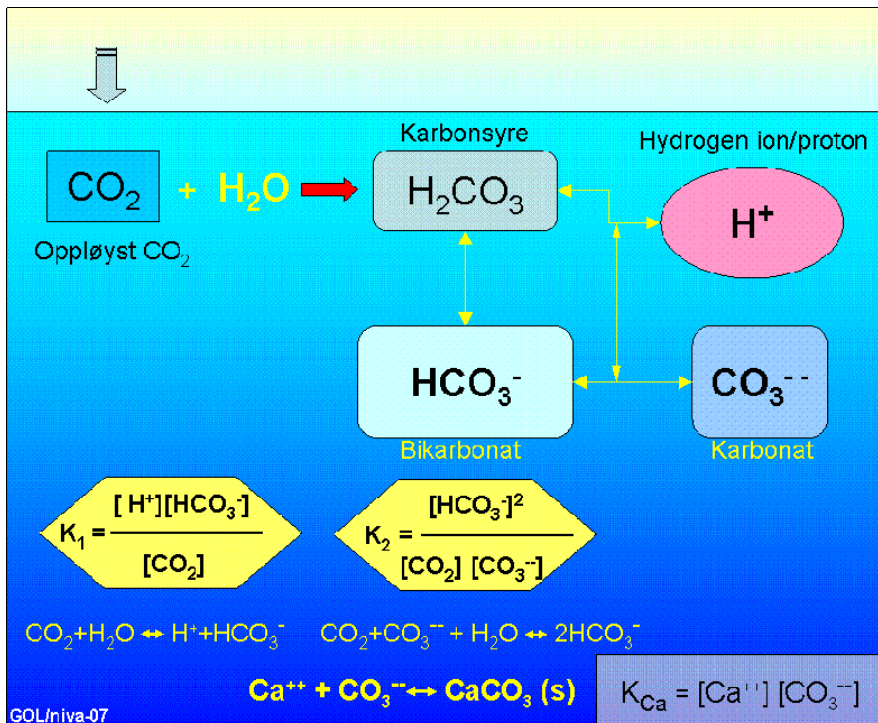


Figure 13. The reactions between CO₂ and seawater with the carbonic acid dissociating via two equilibrium reactions. The calcium reaction represents the situation in the lysocline with 100% saturation of calcium carbonate.

Table 2. The concentration of the most abundant cations and anions in seawater of salinity 35 ppt (‰). Source: Practical handbook. Marine Science. CRD Press, 1994 and Seawater: It's composition, properties and behaviour. Open Univ. Press, 1997.

Cations, g/kg		Anions, g/kg	
Sodium, Na ⁺	10.76	Chloride, Cl ⁻	19.35
Magnesium, Mg ²⁺	1.30	Sulphate, SO ₄ ²⁻	2.71
Calcium, Ca ²⁺	0.41	Bicarbonate, HCO ₃ ⁻	0.15
Potassium, K ⁺	0.40	Bromide, Br ⁻	0.07
Strontium, Sr ²⁺	0.008	Borate, H ₂ BO ₃ ⁻	0.005
		Fluoride, F ⁻	0.001
Sum relative to total salts	12.6 ‰		21.9 ‰

5. Dispersion calculations

5.1 Cormix

Concentrations of residuals of the liquid sodium sulphate discharge were simulated by the model CORMIX-GI. CORMIX was originally developed by EPA in U.S.A.. The model has modules for simulating submerged discharges. The present context represents a submerged discharge, close to the bottom. Ambient current and turbulence determines the fate of the discharge.

The discharge water from the Weyland process will be rapidly diluted with ambient sea water in Sørfolda bay. The physical mechanisms governing the dilution at any time will depend on the actual currents and hydrographic conditions, which will vary somewhat with time.

The exact location of the discharge is not yet determined. We have assumed a discharge depth of 30 m, 400 m from nearest shore.

The ambient water is represented by a linear density stratification, 1022 kg/m³ on the surface and 1025 kg/m³ at the bottom.

The discharged water essentially goes through two stages: One called primary dilution (jet phase), and one for the secondary dilution or dispersion. The first accounts for the processes of dilution in the initial stage until the discharged water interleaves in the water column at its neutrally buoyant level (or at sea surface/bottom). The second takes into consideration the horizontal dispersion due to the water current in the ambient.

The model is based on a set of simple first order differential equations, expressing conservation of momentum and mass during the mixing with stratified ambient water.

Input to the model is one or several (observed) vertical hydrographic profiles of the ambient water, i.e. salinity and temperature versus depth. Then parameters related to the specific discharge are fed into the computer (volume flux, pipe diam. etc.).

Output

The model outputs (for each input scenario) the level of neutral buoyancy for the discharged water, and the associated dilution in the centre of the plume etc. Also given is the overshoot depth (minimum depth in the case of a rising plume) before the neutral situation.

3.3. Secondary dilution

After neutral interleaving of the discharge plume, the discharge water physically will start to spread horizontally. This is the second stage of dilution, which is highly dependent on the current and lateral velocity shear in the ambient recipient. Effect of wind is assumed to stimulate the current and mixing. Surface waves will help to mix the discharge water vertically, and additionally enhance the secondary dilution.

To model the fate of effluents, we have used a simple point-source advection-diffusion model. The simplified formulation is as follows:

$$\partial C / \partial t = -U \partial C / \partial x + K \partial^2 C / \partial x^2 + K \partial^2 C / \partial y^2 + kC + S,$$

where $C(x,y)$ is the effluent concentration, t is time, U is the downstream current velocity (along-shore), K is the horizontal eddy diffusion coefficient, k is the concentration decay constant, and S is the source supply of effluents. In the calculations, k (the decay constant) was set to zero. This is probably realistic for most of the effluents, which will behave as conservative substances, while for the suspended material, it may be a simplification. Parameters such as pH may not behave conservatively, but undergo (chemical) transitions during the fluid transport downstream. Other substances may undergo precipitation or flocculation. It is beyond the scope of the present study to validate these latter effects.

The time for the buoyant plume from the pipe to reach its neutral level will probably be of order half a minute or less (mostly depending on discharge actual stratification in the ambient fjord). During this time period the plume will be displaced horizontally only a small distance (a few meters) in the direction of the main currents.

During the primary dilution process, the plume will grow wider. In the neutral position the plume width in the cross-current direction will be on order of the difference in depth from the discharge. Actual current conditions will then determine the shape of the influence area, as the discharge water spreads horizontally. With weak or zero current (e.g. during tidal peaks) the discharge plume will spread out radially to all directions.

Probably the radially symmetric case will be a non-typical situation. The typical situation will be the discharge water spreading in a prolonged plume, possibly parallel to the shoreline. The typical current speed may probably be ca 5-10 cm/s at the site in Sørfolda bay.

As the discharge is carried away from the discharge site, it is continuously diluted by lateral and vertical turbulent diffusion. Some discharge parameters, such as pH may be regarded as to behave in a non-conservative manner in the recipient, i.e. they are not dispersed due to turbulence and mixing only. The effects of such secondary processes have not been calculated explicitly.

Tables 3, 4 and 5 show results from the computations with CORMIX. See the following discussion about the results.

Table 3. Session report, extract. from CORMIX run with discharge density of 1005 kg/m³. The full results are in the Appendix.

```

CORMIX SESSION REPORT:
XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX
                CORMIX: CORNELL MIXING ZONE EXPERT SYSTEM
                CORMIX-GI Version 4.1GT
SITE NAME/LABEL:      Future discharge
  DESIGN CASE:        Weyland Sørsalten Na2SO4
  FILE NAME:          D:\CORMIX-GI\Weyland-I.1005.prd
Using subsystem CORMIX1: Submerged Single Port Discharges
  Start of session:   11/28/2011--00:36:22
*****
SUMMARY OF INPUT DATA:
-----
AMBIENT PARAMETERS:
  Cross-section                = unbounded
  Average depth                HA   = 35 m
  Depth at discharge           HD   = 30 m
  Ambient velocity             UA   = 0.05 m/s
  Darcy-Weisbach friction factor F   = 0.2401
    Calculated from Manning's n     = 0.1
  Wind velocity               UW   = 7 m/s
Stratification Type           STRCND = A
  Surface density             RHOAS = 1022 kg/m^3
  Bottom density             RHOAB = 1025 kg/m^3
-----
DISCHARGE PARAMETERS:      Submerged Single Port Discharge
  Nearest bank                = left
  Distance to bank            DISTB = 400 m
  Port diameter               D0    = 0.3 m
  Port cross-sectional area   A0    = 0.0707 m^2
  Discharge velocity          U0    = 0.18 m/s
  Discharge flowrate         Q0    = 0.013 m^3/s
  Discharge port height      H0    = 2 m
  Vertical discharge angle    THETA = 0 deg
  Horizontal discharge angle  SIGMA = 270 deg
  Discharge density          RHO0   = 1005 kg/m^3
  Density difference          DRHO   = 19.8000 kg/m^3
  Buoyant acceleration       GP0    = 0.1895 m/s^2
  Discharge concentration    C0     = 100 mg/l
  Surface heat exchange coeff. KS   = 0 m/s
  Coefficient of decay       KD     = 0 /s
-----

```


Table 4. Prediction of the plume dispersion from the case with **1005 kg/m³** density. The Z-coordinate indicate distance from the discharge nozzle at the bottom, upwards. See the session report in Appendix.

Primary dilution:

X	Y	Z	S	C	B
0.00	0.00	2.00	1.0	0.100E+03	0.15
0.00	-0.05	2.00	1.0	0.100E+03	0.15
Minimum jet height has been reached.					
0.27	-0.51	3.40	3.8	0.261E+02	0.23
0.70	-0.63	4.90	9.5	0.105E+02	0.41
1.23	-0.70	6.35	17.3	0.577E+01	0.59
1.89	-0.75	7.77	27.7	0.361E+01	0.81
2.69	-0.79	9.12	40.1	0.249E+01	1.07
3.65	-0.82	10.33	52.9	0.189E+01	1.35
4.90	-0.85	11.26	69.4	0.144E+01	1.73
Maximum jet height has been reached.					
6.41	-0.88	11.49	78.1	0.128E+01	1.91
7.87	-0.91	10.94	87.3	0.115E+01	1.95
9.20	-0.93	10.15	103.0	0.971E+00	2.12
9.22	-0.93	10.14	103.0	0.971E+00	2.12

Terminal level in stratified ambient has been reached.

Cumulative travel time = 97. sec

Secondary dilution:

Profile definitions:

BV = top-hat thickness, measured vertically

BH = top-hat half-width, measured horizontally in Y-direction

ZU = upper plume boundary (Z-coordinate)

ZL = lower plume boundary (Z-coordinate)

S = hydrodynamic average (bulk) dilution

C = average (bulk) concentration (includes reaction effects, if any)

Plume Stage 1 (not bank attached):

X	Y	Z	S	C	BV	BH	ZU	ZL
13.52	-0.93	10.14	132.6	0.754E+00	2.00	8.62	11.14	9.14
87.91	-0.93	10.14	314.9	0.318E+00	0.93	44.26	10.60	9.68
162.30	-0.93	10.14	598.4	0.167E+00	1.02	75.99	10.65	9.63
236.68	-0.93	10.14	955.0	0.105E+00	1.12	110.46	10.70	9.58
311.07	-0.93	10.14	1372.7	0.729E-01	1.21	147.30	10.74	9.53
385.46	-0.93	10.14	1844.9	0.542E-01	1.29	186.11	10.78	9.49
459.84	-0.93	10.14	2367.1	0.422E-01	1.36	226.58	10.82	9.46
534.23	-0.93	10.14	2935.4	0.341E-01	1.42	268.45	10.85	9.43
608.61	-0.93	10.14	3547.0	0.282E-01	1.48	311.57	10.88	9.40
683.00	-0.93	10.14	4199.1	0.238E-01	1.53	355.76	10.91	9.37
757.39	-0.93	10.14	4889.6	0.205E-01	1.59	400.92	10.93	9.35

Cumulative travel time = 15060. sec

Table 5. Prediction of the plume dispersion from the case with **1010 kg/m³** density. The Z-coordinate indicate distance from the discharge nozzle at the bottom, upwards. See the session report in Appendix.

Primary dilution:

X	Y	Z	S	C	B
0.00	0.00	2.00	1.0	0.100E+03	0.15
0.00	-0.06	1.99	1.0	0.100E+03	0.15
Minimum jet height has been reached.					
0.29	-0.57	3.26	3.4	0.293E+02	0.23
0.73	-0.72	4.65	8.2	0.122E+02	0.39
1.29	-0.80	5.99	14.9	0.670E+01	0.57
1.98	-0.86	7.31	23.9	0.418E+01	0.79
2.80	-0.90	8.52	34.7	0.288E+01	1.04
3.80	-0.94	9.58	46.2	0.216E+01	1.31
5.06	-0.97	10.34	59.7	0.167E+01	1.64
Maximum jet height has been reached.					
6.50	-1.01	10.47	65.7	0.152E+01	1.76
7.87	-1.03	9.99	73.7	0.136E+01	1.81
9.17	-1.06	9.31	86.6	0.115E+01	1.97
Terminal level in stratified ambient has been reached.					
Cumulative travel time =			99. sec		

Secondary dilution:

Profile definitions:

- BV = top-hat thickness, measured vertically
- BH = top-hat half-width, measured horizontally in Y-direction
- ZU = upper plume boundary (Z-coordinate)
- ZL = lower plume boundary (Z-coordinate)
- S = hydrodynamic average (bulk) dilution
- C = average (bulk) concentration (includes reaction effects, if any)

Plume Stage 1 (not bank attached):

X	Y	Z	S	C	BV	BH	ZU	ZL
12.91	-1.06	9.31	110.4	0.905E+00	1.92	7.49	10.27	8.35
88.11	-1.06	9.31	288.6	0.346E+00	0.90	41.69	9.76	8.86
163.31	-1.06	9.31	570.4	0.175E+00	1.01	73.26	9.81	8.80
238.51	-1.06	9.31	926.2	0.108E+00	1.12	107.85	9.87	8.75
313.70	-1.06	9.31	1344.6	0.744E-01	1.21	144.93	9.91	8.71
388.90	-1.06	9.31	1819.1	0.550E-01	1.28	184.06	9.95	8.67
464.10	-1.06	9.31	2344.7	0.426E-01	1.36	224.89	9.99	8.63
539.30	-1.06	9.31	2917.7	0.343E-01	1.42	267.18	10.02	8.60
614.50	-1.06	9.31	3534.9	0.283E-01	1.48	310.73	10.05	8.57
689.69	-1.06	9.31	4193.6	0.238E-01	1.53	355.39	10.08	8.54
764.89	-1.06	9.31	4891.5	0.204E-01	1.59	401.05	10.10	8.52
Cumulative travel time =			15214. sec					

5.2 Discussion

In a typical situation the discharge water will interleave somewhere between 2 m and 11-12 m above the bottom (release point). Clearance to the surface is thus about 18 m. The heavier discharge gives about 1 m deeper neutral depth/interleaving, i.e., no significant impact on the dispersion, compared to the lighter case.

Upon interleaving at its neutrally buoyant level, the dilution factor will be about 60-70, i.e. 1 unit volume of discharge mixed with 60-70 volumes of ambient (fjord) water.

A winter situation with weaker stratification in the fjord than we have anticipated, will probably give somewhat shallower interleaving.

We have calculated the horizontal dispersion based on a modest dispersion coefficient. This conservative size will represent conditions with weak current shear (weak turbulence), and as such represents the "worst case" in terms of mixing efficiency in the recipient. Actual dispersion conditions will vary with time. At any rate it is difficult to assess the true dispersion without supporting field measurements such as colour or tracer studies.

Only the near-field (< 1 km distance downstream) is shown, with dilution (S) rapidly increasing away from the discharge location. It must be noted that the fields and factors shown represent dilution of the discharge water after interleaving, i.e. after it has undergone the primary dilution phase described previously. According to the primary dilution calculations the dilution factors already had reached 60-70 before the process of secondary dispersion starts.

A submerged discharge at 30 m depth from the Weyland plant for the liquid discharge of Na₂SO₄ with the stated flux of ca 50 m³/hr totally (solvent + solute) seems to give satisfactory dispersion in the marine recipient Sørfolda bay.

5.2.1 Chemical reactions in the fjord water

The two major constituents Na⁺ and SO₄⁼ in the discharge both are among major cations and anions, respectively, in seawater. As such, they will not represent any new, possibly harmful foreign species. The concentration in the discharge is also relatively small, albeit higher than in the ambient. Calcium is the most susceptible among the major cations in seawater to associate in ion-pairs, and possibly precipitate. About 8-10 % of Ca⁺⁺ cations in seawater are in the associated form, 88% in free form, and about 1% as carbonate. So in principle, Ca⁺⁺ is a candidate to associate more and possibly precipitate as a response to the added Na⁺ that will increase the total ion strength of the seawater mixture. CaSO₄ association is the most likely scenario, by either association with free Ca⁺⁺ or derive Ca⁺⁺ from either dissolved or solid (mineral, shells) CaCO₃.

CaSO₄ does not precipitate naturally in normal, oxygenated seawater. In semi-enclosed seas like the Persian Gulf with high evaporation and high salinity deep water, this may actually take place (Brooker and Peng 1998). As there is relatively much more free Ca⁺⁺ in normal seawater, the likely source will be free Ca⁺⁺, as it is the most abundant. It is unlikely that the process will deprive the seawater from any significant amounts of calcium carbonate (surface seawater is supersaturated with CaCO₃), and even less at risk will be the shells and minerals on the seabed, as the discharge water most likely will interleave in the water column.

The lower pH in the discharge (pH=6) may be another factor to take into consideration, as it will tend to increase the CO₂ concentration and reduce the carbonate concentration (Bjerrum relation). This should tend to release associated Ca⁺⁺ from CO₃⁼, this increase the available free Ca⁺⁺ that may be

available to associate with $\text{SO}_4^{=}$. Again, this will involve dissolved and minor suspended particulate carbonate in the water column, not on the seabed where most biota are found.

So as a first order assessment, we do not see any serious issues related to the discharge of Na_2SO_4 and calcium/carbonate in relation to biota. However, the total picture is quite complex and should be studied in more detail if the plans for establishing the factory at Sørsalten will proceed. This should also include experimental work and modelling estimates of the reaction kinetics involved, as much as possible.

5.3 Recommended follow-up

A more detailed design of the discharge and refined calculations based on actually measured data from the fjord should be made prior to a final decision on locating the discharge.

The discharge area should undergo an ecological survey as a baseline investigation, before the discharge is established. The same will apply for a site for the disposal of CaSO_4 , if that scenario is selected.

Also, an environmental assessment should be made for the selected scenario, prior to any final decision on the discharge or disposal site.

6. References

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7. Appendix

List of results from the CORMIX run.

Density 1005 kg/m³:

CORMIX SESSION REPORT:
 XX
 CORMIX: CORNELL MIXING ZONE EXPERT SYSTEM
 CORMIX-GI Version 4.1GT

SITE NAME/LABEL: Future discharge
 DESIGN CASE: Weyland Sørsalten Na2SO4
 FILE NAME: D:\CORMIX-GI\Weyland-I.1005.prd
 Using subsystem CORMIX1: Submerged Single Port Discharges
 Start of session: 11/28/2011--00:36:22

SUMMARY OF INPUT DATA:

AMBIENT PARAMETERS:

Cross-section		= unbounded
Average depth	HA	= 35 m
Depth at discharge	HD	= 30 m
Ambient velocity	UA	= 0.05 m/s
Darcy-Weisbach friction factor	F	= 0.2401
Calculated from Manning's n		= 0.1
Wind velocity	UW	= 7 m/s
Stratification Type	STRCND	= A
Surface density	RHOAS	= 1022 kg/m ³
Bottom density	RHOAB	= 1025 kg/m ³

DISCHARGE PARAMETERS: Submerged Single Port Discharge

Nearest bank		= left
Distance to bank	DISTB	= 400 m
Port diameter	D0	= 0.3 m
Port cross-sectional area	A0	= 0.0707 m ²
Discharge velocity	U0	= 0.18 m/s
Discharge flowrate	Q0	= 0.013 m ³ /s
Discharge port height	H0	= 2 m
Vertical discharge angle	THETA	= 0 deg
Horizontal discharge angle	SIGMA	= 270 deg
Discharge density	RHO0	= 1005 kg/m ³
Density difference	DRHO	= 19.8000 kg/m ³
Buoyant acceleration	GP0	= 0.1895 m/s ²
Discharge concentration	C0	= 100 mg/l
Surface heat exchange coeff.	KS	= 0 m/s
Coefficient of decay	KD	= 0 /s

DISCHARGE/ENVIRONMENT LENGTH SCALES:

LQ = 0.27 m	Lm = 0.98 m	Lb = 19.71 m
LM = 0.22 m	Lm' = 1.26 m	Lb' = 3.02 m

NON-DIMENSIONAL PARAMETERS:

Port densimetric Froude number	FR0	= 0.77
Velocity ratio	R	= 3.68

MIXING ZONE / TOXIC DILUTION ZONE / AREA OF INTEREST PARAMETERS:

Toxic discharge	= no
Water quality standard specified	= no
Regulatory mixing zone	= no
Region of interest	= 2500 m downstream

For density 1005 kg/m³, continued:

HYDRODYNAMIC CLASSIFICATION:

| FLOW CLASS = S5 |

This flow configuration applies to a layer corresponding to the linearly stratified density layer at the discharge site.

Applicable layer depth = water depth = 30 m

MIXING ZONE EVALUATION (hydrodynamic and regulatory summary):

X-Y-Z Coordinate system:

Origin is located at the bottom below the port center:

400 m from the left bank/shore.

Number of display steps NSTEP = 10 per module.

NEAR-FIELD REGION (NFR) CONDITIONS :

Note: The NFR is the zone of strong initial mixing. It has no regulatory implication. However, this information may be useful for the discharge designer because the mixing in the NFR is usually sensitive to the discharge design conditions.

Pollutant concentration at edge of NFR = 0.7542 mg/l

Dilution at edge of NFR = 132.6

NFR Location: x = 13.52 m

(centerline coordinates) y = -0.93 m

z = 10.14 m

NFR plume dimensions: half-width = 8.62 m

thickness = 2.00 m

Buoyancy assessment:

The effluent density is less than the surrounding ambient water density at the discharge level.

Therefore, the effluent is POSITIVELY BUOYANT and will tend to rise towards the surface.

Stratification assessment:

The specified ambient density stratification is dynamically important.

The discharge near field flow is trapped within the linearly stratified ambient density layer.

UPSTREAM INTRUSION SUMMARY:

Plume exhibits upstream intrusion due to low ambient velocity or strong discharge buoyancy.

Intrusion length = 4.43 m

Intrusion stagnation point = 4.79 m

Intrusion thickness = 3.88 m

Intrusion half width at impingement = 8.62 m

Intrusion half thickness at impingement = 2.00 m

PLUME BANK CONTACT SUMMARY:

Plume in unbounded section contacts nearest bank at 757.39 m downstream.

***** TOXIC DILUTION ZONE SUMMARY

No TDZ was specified for this simulation.

***** REGULATORY MIXING ZONE SUMMARY

No RMZ and no ambient water quality standard have been specified.

For density 1010 kg/m³:

CORMIX SESSION REPORT:
 XXX

CORMIX: CORNELL MIXING ZONE EXPERT SYSTEM
 CORMIX-GI Version 4.1GT

SITE NAME/LABEL: Future discharge
 DESIGN CASE: Weyland Sørsalten Na2SO4
 FILE NAME: D:\CORMIX-GI\Weyland-I.prd
 Using subsystem CORMIX1: Submerged Single Port Discharges
 Start of session: 11/28/2011--00:29:16

SUMMARY OF INPUT DATA:

 AMBIENT PARAMETERS:

Cross-section		= unbounded
Average depth	HA	= 35 m
Depth at discharge	HD	= 30 m
Ambient velocity	UA	= 0.05 m/s
Darcy-Weisbach friction factor	F	= 0.2401
Calculated from Manning's n		= 0.1
Wind velocity	UW	= 7 m/s
Stratification Type	STRCOND	= A
Surface density	RHOAS	= 1022 kg/m ³
Bottom density	RHOAB	= 1025 kg/m ³

 DISCHARGE PARAMETERS:

Submerged Single Port Discharge

Nearest bank		= left
Distance to bank	DISTB	= 400 m
Port diameter	D0	= 0.3 m
Port cross-sectional area	A0	= 0.0707 m ²
Discharge velocity	U0	= 0.18 m/s
Discharge flowrate	Q0	= 0.013 m ³ /s
Discharge port height	H0	= 2 m
Vertical discharge angle	THETA	= -5 deg
Horizontal discharge angle	SIGMA	= 270 deg
Discharge density	RHO0	= 1010 kg/m ³
Density difference	DRHO	= 14.8000 kg/m ³
Buoyant acceleration	GP0	= 0.1416 m/s ²
Discharge concentration	C0	= 100 mg/l
Surface heat exchange coeff.	KS	= 0 m/s
Coefficient of decay	KD	= 0 /s

 DISCHARGE/ENVIRONMENT LENGTH SCALES:

LQ = 0.27 m	Lm = 0.98 m	Lb = 14.73 m
LM = 0.25 m	Lm' = 1.26 m	Lb' = 2.81 m

 NON-DIMENSIONAL PARAMETERS:

Port densimetric Froude number	FRO	= 0.89
Velocity ratio	R	= 3.68

 MIXING ZONE / TOXIC DILUTION ZONE / AREA OF INTEREST PARAMETERS:

Toxic discharge	= no
Water quality standard specified	= no
Regulatory mixing zone	= no
Region of interest	= 2500 m downstream

For density 1005 kg/m³, continued:

HYDRODYNAMIC CLASSIFICATION:

```
*-----*
| FLOW CLASS   = S5 |
*-----*
```

This flow configuration applies to a layer corresponding to the linearly stratified density layer at the discharge site.
 Applicable layer depth = water depth = 30 m

MIXING ZONE EVALUATION (hydrodynamic and regulatory summary):

 X-Y-Z Coordinate system:

Origin is located at the bottom below the port center:
 400 m from the left bank/shore.
 Number of display steps NSTEP = 10 per module.

 NEAR-FIELD REGION (NFR) CONDITIONS :

Note: The NFR is the zone of strong initial mixing. It has no regulatory implication. However, this information may be useful for the discharge designer because the mixing in the NFR is usually sensitive to the discharge design conditions.

Pollutant concentration at edge of NFR = 0.9055 mg/l
 Dilution at edge of NFR = 110.4
 NFR Location: x = 12.91 m
 (centerline coordinates) y = -1.06 m
 z = 9.31 m
 NFR plume dimensions: half-width = 7.49 m
 thickness = 1.92 m

 Buoyancy assessment:

The effluent density is less than the surrounding ambient water density at the discharge level.
 Therefore, the effluent is POSITIVELY BUOYANT and will tend to rise towards the surface.

 Stratification assessment:

The specified ambient density stratification is dynamically important.
 The discharge near field flow is trapped within the linearly stratified ambient density layer.

 UPSTREAM INTRUSION SUMMARY:

Plume exhibits upstream intrusion due to low ambient velocity or strong discharge buoyancy.
 Intrusion length = 3.64 m
 Intrusion stagnation point = 5.53 m
 Intrusion thickness = 3.88 m
 Intrusion half width at impingement = 7.49 m
 Intrusion half thickness at impingement = 1.92 m

 PLUME BANK CONTACT SUMMARY:

Plume in unbounded section contacts nearest bank at 764.89 m downstream.
 ***** TOXIC DILUTION ZONE SUMMARY *****
 No TDZ was specified for this simulation.
 ***** REGULATORY MIXING ZONE SUMMARY *****
 No RMZ and no ambient water quality standard have been specified.
 ***** FINAL DESIGN ADVICE AND COMMENTS *****

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