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D-SLE

Sea Lock Formulation

User Manual

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1 A guide to this manual

1.1 Introduction

This User Manual describes D-SLE, which is a Deltares library to calculate salt intrusion through shipping locks. This library can be coupled to external modules like the hydrodynamic module D-Flow Flexible Mesh (D-Flow FM), which is part of the Delft3D Flexible Mesh Suite or D-HYDRO Suite.

The user manual covers:

- How to use the D-SLE shared and static libraries from a C application.
- How to prepare steady-state and phase-wise calculations.
- The theory on which D-SLE is based, serving as background information on the inner workings of the D-SLE core.
- An overview of the C API used to embed D-SLE in other software.
- An example of how to couple a D-Flow FM application to D-SLE, which has also described in Section (Deltares, 2026, **??**) as well.

Note

D-SLE was previously known as ZSF, an abbreviation for the Dutch name “Zeesluisformulering”. ZSF remains in some legacy API identifiers and image filenames, but D-SLE is the current product name.

1.2 Status of D-SLE

The coupling of D-Flow FM to D-SLE of TRL level 4-6 (prototype), with the definitions of the Technical Technology Readiness Levels (TRL) in Section 1.3.

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1.3 Deltares Software Development Canvas

For high quality, dependable and future proof of Deltares' software, the **Deltares Software Development Canvas** is applied. The canvas provides a consistent way to classify the maturity of our software products and prototypes, so that teams, strategic partners and clients, and other stakeholders know exactly what a release does—and does not—offer at any given moment software evolves through several stages: from the first idea, to experimentation, to prototypes, to stable releases, to fully mature products, and eventually—when the time comes—to phase out and replacement. Together, these stages form the software lifecycle. The Deltares Software Development Canvas describes these stages in a clear, recognisable way, making it easy to see where a product stands and what that means for its use in projects, research, or collaboration with partners and clients. Below is a brief overview of the five levels in the Deltares software lifecycle, based on the widely used Technology Readiness Level (TRL) framework:

- **Concept (TRL 1–3)**; This stage covers early ideas and experimental models, which is relevant for scientific code, new methods or exploratory prototypes. These concepts are not yet validated or supported, and pre compiled versions are only available under Pre Release Terms and Conditions. This phase is ideal for research and experimentation, helping us explore promising directions before investing in full product development.
- **Prototype (TRL 4–6)**; Prototypes are used in pilots and internal projects. They are field tested, iteratively improved and shared with a small network of strategic partners and clients. Pre compiled prototypes still fall under Pre Release Terms and Conditions. Feedback is crucial at this stage to understand their real world potential. This is where early ideas start maturing into viable software solutions.
- **Stable (TRL 7–8)**; Stable releases offer fully validated, reliable functionality tailored to specific use cases or regions. Pre compiled stable releases are supported for key accounts and partners under the Stable Release Terms and Conditions; others may still access them under Pre Release Terms and Conditions. This marks the transition from development to operational readiness, where software becomes robust and dependable.
- **General Available (GA) (TRL 9)**; GA software is widely adopted, internationally validated and fully supported. Pre compiled GA releases are available through standard licensing or service packages under GA Terms and Conditions. Achieving GA requires consistent performance across diverse contexts and organisational readiness for structured maintenance and support.
- **End of Life (EoL) and renewal**; Eventually, software reaches a point where maintenance is no longer viable or where a successor is ready. EoL marks the beginning of phasing out or replacing the software, ensuring Deltares continues to offer modern, secure and sustainable digital solutions.

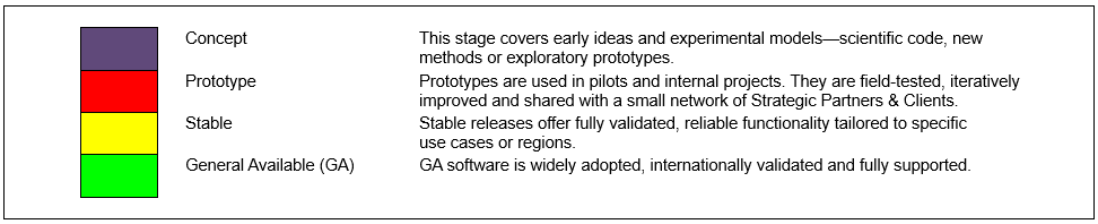

Fig. 1: *Overview of TRL levels for software of Deltares*

2 Getting Started

2.1 D-SLE libraries

D-SLE is delivered as a C library for use by the suite components and by other applications. The current repository build produces the shared library `dsle.dll` and the static library `dsle-static`.

The public interface is declared in `dsle.h`. Applications using the shared library must make the DLL available at run time. Applications using the static library must link the library and its required dependencies according to the build configuration.

2.2 First calculation

Include `dsle.h` and initialize a parameter structure with `dsle_param_default`. Set the lock geometry, operating conditions, water levels, salinities, temperatures, and optional mitigation parameters before calling `dsle_calc_steady`.

For a phase-wise calculation, initialize `dsle_phase_state_t` with `dsle_initialize_state` and call the phase-step functions in order. The functions return an integer status code. Use `dsle_error_msg` to obtain the corresponding message when a call does not succeed.

2.3 Building from the repository

The D-SLE C package is located under `src/engines_gpl/dsle/packages` in the D-Hydro repository. Its CMake targets are `dsle` for the shared library and `dsle-static` for the static library.

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3 Coupling through DIMR

D-SLE can be coupled to D-Flow FM through the Deltares Integrated Model Runner (DIMR). This chapter describes the D-SLE side of that coupling: the component configuration, the exchanged variables, the D-SLE input files, and the DIMR representation of temperature and passive constituents. The D-Flow FM manual describes the FM mesh, dry points, polygons, laterals, and the distribution of exchanged values over FM cells.

3.1 Coupled model

A coupled model contains a D-Flow FM component and a D-SLE component. D-Flow FM supplies the water level and concentrations at the lake and sea sides of each lock. D-SLE returns the discharges and concentrations that D-Flow FM applies through its laterals. A separate inflow and outflow lateral at each side of the lock is recommended to prevent unphysical mixing in the FM model.

D-SLE is loaded by DIMR as the `dsle` library. A minimal component definition is:

```
<component name="SeaLockExchange">
  <library>dsle</library>
  <workingDir>dsle</workingDir>
  <inputFile>sealock_A.ini</inputFile>
</component>
```

The D-Flow FM component is configured separately with its own library, working directory, and `.mdu` input file. The DIMR control section starts both components and connects them through two couplers: one from D-Flow FM to D-SLE and one from D-SLE to D-Flow FM. The exchange interval must be compatible with the D-SLE operational time series and with the FM time step configuration.

3.2 D-SLE input files

At least one D-SLE `.ini` file and one operational-parameter `.csv` file are required for a coupled simulation. For multiple locks, define one `[sealock]` section and one operational-parameter file per lock.

The following keys are read by the current D-SLE implementation:

```
[general]
start_time       = 200101010000
end_time         = 200101020000   # optional
kmx              = 5              # number of FM layers
log_level        = info

[sealock]
id                              = sealock_A
computation_mode                = phase_wise
sealock_operational_parameters = sealock_A.csv
initial_head_lock               = 0.0
initial_salinity_lock           = 10.0
initial_saltmass_lock            = 0.0
initial_temperature_lock        = 6.0
initial_volume_ship_in_lock     = 0.0
lock_length                     = 300.0
lock_width                      = 25.0
lock_bottom                     = -7.0
```

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```
flow_profile                    = 1, 0, 0, 0, 0, 0, -1
allowed_head_difference         = 0.1
```

The `computation_mode` is either `cycle_average` or `phase_wise`. The `flow_profile` is used for layer-wise discharge distribution in a 3D coupling and must have a supported sign change between extraction and injection layers. The `kmx` value must not exceed the number of layers configured for the FM model.

D-SLE reads the operational time series from the CSV file named by `sealock_operational_parameters`. The timestamp format is `YYYYMMDDhhmm`; for example, `200101010000` denotes 1 January 2001 at 00:00. The first time in the time series must not be later than the configured start time, timestamps must be strictly increasing, and the DIMR update interval must be compatible with the available phase durations.

3.2.1 Operational CSV files

Operational CSV files use a semicolon (`;`) as the separator and must contain a header row. The required columns depend on `computation_mode`. All time, duration, volume, discharge, distance, sill-height, and density-current-factor values are numeric.

For `cycle_average`, use the following columns:

```
time; ship_volume_lake_to_sea; ship_volume_sea_to_lake; door_time_to_open;
leveling_time; density_current_factor_sea; density_current_factor_lake;
num_cycle; flushing_discharge
```

The `flushing_discharge` value is applied to both tide conditions by the current implementation. The column name is `num_cycle` (singular), although it populates the `num_cycles` model parameter.

For `phase_wise`, use the following columns:

```
time; routine; ship_volume_lake_to_sea; ship_volume_sea_to_lake;
t_flushing; t_level; t_open_lake; t_open_sea;
density_current_factor_lake; density_current_factor_sea;
distance_door_bubble_screen_lake; distance_door_bubble_screen_sea;
flushing_discharge_high_tide; flushing_discharge_low_tide;
sill_height_lake; sill_height_sea
```

The `routine` value selects the phase: values 1 through 4 select the four locking phases, while a negative value selects flushing with the doors closed. For routines 1 through 4, the active duration is respectively `t_level`, `t_open_lake`, `t_level`, or `t_open_sea`. For a negative routine, the active duration is `t_flushing`.

Example of a cycle-average data row:

```
time;ship_volume_lake_to_sea;ship_volume_sea_to_lake;door_time_to_open;leveling_time;
    density_current_factor_sea;density_current_factor_lake;num_cycle;
    flushing_discharge
202510221200.0;1.0;2.0;300.0;300.0;1.0;1.0;12.0;0.0
```

Example of a phase-wise data row:

```
time;routine;ship_volume_lake_to_sea;ship_volume_sea_to_lake;t_flushing;t_level;
    t_open_lake;t_open_sea;density_current_factor_lake;density_current_factor_sea;
    distance_door_bubble_screen_lake;distance_door_bubble_screen_sea;
    flushing_discharge_high_tide;flushing_discharge_low_tide;sill_height_lake;
    sill_height_sea
202510221200.0;1;0.0;0.0;0.0;300.0;0.0;0.0;1.0;1.0;0.0;0.0;0.0;0.0;0.0;0.0
```

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3.2.2 Flow profile and layer distribution

In a 3D coupling, `flow_profile` distributes a total D-SLE discharge over the active FM layers. The comma-separated values describe a piecewise-linear profile over relative depth from 0 to 1. The first and last values must have opposite signs, so the profile has one transition between extraction and injection. The implementation rejects profiles without exactly one zero crossing or with an invalid sign pattern between the endpoints.

The positive and negative parts are normalized independently to unit magnitude before the profile is applied. For example, a five-position profile can be written as:

```
flow_profile = 1.0, 0.5, 0.0, -0.5, -1.0
```

The profile is then integrated over the active layer volumes. A 2D model uses a default single-layer distribution and does not require a custom profile.

3.3 DIMR variable exchange

D-SLE accepts DIMR/BMI keys in the form:

```
<variable_type>/<lock_id>/<quantity>
```

The variable type is normally `dsle_boundary_condition` for values supplied to D-SLE and `results` for values returned by D-SLE. The lock ID is the `id` from the corresponding `[sealock]` section.

3.3.1 Values supplied to D-SLE

The following quantities can be set for each lock:

```
dsle_boundary_condition/<id>/head_lake
 dsle_boundary_condition/<id>/head_sea
dsle_boundary_condition/<id>/salinity_lake
dsle_boundary_condition/<id>/salinity_sea
dsle_boundary_condition/<id>/temperature_lake
dsle_boundary_condition/<id>/temperature_sea
```

For a 3D coupling, the following quantities are arrays with one value per active layer:

```
dsle_boundary_condition/<id>/water_volume_from_lake
dsle_boundary_condition/<id>/water_volume_to_lake
dsle_boundary_condition/<id>/water_volume_from_sea
dsle_boundary_condition/<id>/water_volume_to_sea
```

Temperature is supplied as a scalar boundary value and is distributed over the active layers internally. Passive constituents use the following keys, where `name` is the FM constituent name:

```
dsle_boundary_condition/<id>/constituent_lake_<name>
dsle_boundary_condition/<id>/constituent_sea_<name>
```

3.3.2 Values returned by D-SLE

D-SLE returns the following scalar or layer-wise quantities:

```
results/<id>/mass_transport_lake
results/<id>/salt_load_lake
results/<id>/discharge_from_lake
results/<id>/discharge_to_lake
```

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```
results/<id>/salinity_to_lake
results/<id>/mass_transport_sea
results/<id>/salt_load_sea
results/<id>/discharge_from_sea
results/<id>/discharge_to_sea
results/<id>/salinity_to_sea
results/<id>/temperature_to_lake
results/<id>/temperature_to_sea
results/<id>/constituent_to_lake_<name>
results/<id>/constituent_to_sea_<name>
```

The discharge and concentration results are layer-wise when the corresponding FM lateral has multiple active layers. In a 2D model they have one active layer. D-Flow FM applies these values to its laterals; the FM-side aggregation and distribution rules are documented in the D-Flow FM User Manual.

A compact DIMR coupler item therefore has the following form:

```
<item type="pointer">
  <sourceName>results/<lock>/discharge_to_lake</sourceName>
  <targetName>laterals/<lateral>/water_discharge</targetName>
</item>
<item type="pointer">
  <sourceName>laterals/<lateral>/outgoing/water_level</sourceName>
  <targetName>dsle_boundary_condition/<lock>/head_lake</targetName>
</item>
```

Use pointer exchange for layer-wise arrays and other values where the DIMR configuration requires pointer semantics. The exact FM lateral IDs are model-specific.

The complete two-way DIMR configuration, including both couplers and the D-Flow FM lateral mappings, is maintained in the D-Flow FM User Manual in the section “Coupling with module for Sea Lock Exchange”. See the published D-Flow FM User Manual for the full example.

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4 Theory

4.1 Introduction

4.1.1 Motivation and goals

The Directorate-General for Public Works and Water Management (Dutch: Rijkswaterstaat), but also other private and public parties around the world in charge of water reserves, would like to calculate the influence of the salt intrusion through shipping locks on the salinity of the fresh water at a reasonable distance from the lock. For example, to calculate the salinity of the water that farmers use to irrigate their land. Such calculations should be able to consider a long period of time and area, as the spread and build-up of salt can take months or years. It is also necessary to be able to consider multiple economical- and climate scenarios, along with the possible measures both on the shipping lock itself and those elsewhere in the system. For this reason, there is a need to have a fast and compact formulation of the processes on the lock, such that this formulation can be used inside a far-field model that models the spread. Such a formulation can then also be used to calculate the transport of water and salt through a shipping lock in a stand-alone fashion (i.e. without coupling it to- or incorporating it in a far-field model).

4.1.2 Approach

The chosen approach for the D-SLE is to set up the equations that describe the flows into and out of the lock, for all phases of the locking cycle. Concretely, this means the volumes due leveling, the lock exchange process, ship displacement, and flushing discharges through the lock chamber. Note that this phase-wise approach is opposed to a fixed time-step approach.

In case registrations of the door movements are available, one can calculate per locking phase what the transports of water and salt are in that particular phase over both lock heads (salt side and fresh side). That way one can calculate based on historical registrations what the salt transport has been.

When no registrations are available, a cycle-averaged transport of salt and water can be calculated based on a few key parameters of the lock operation. These parameters are then translated into a repeating pattern of locking phases, i.e. when the door is open and how long leveling is supposed to take. Then, the transports of water and salt per phase can be added up, leading to cycle-averaged values of the transports. These averaged values can then serve as in a forcing in a far-field model.

An overview of the concept of the D-SLE model is given in figure below. A more detailed discussion of all the physical quantities involved will be explained later. What is visible is that the boundary conditions of the model are the temperature, salinity and water level on each side of the lock. These boundary conditions, together with the geometry and operation of the lock, determine the discharge that go into the lock with the governing salinity, and out of the lock with a salinity in the lock chamber that follows from the locking process. The flows into the lock chamber are a withdrawal from the approach harbor on each side of the lock, Q_F^- and Q_S^-, and the flows going out of the lock are discharges to the approach harbors, Q_F^+ and Q_S^+.

4.2 Processes and definitions

To set up the equations, it is necessary to define the various physical quantities. An understanding of these physical quantities should be based on an understanding of the relevant processes. Therefore, we first (briefly) introduce these processes, followed by explaining the quantities that will appear in the equations later on.

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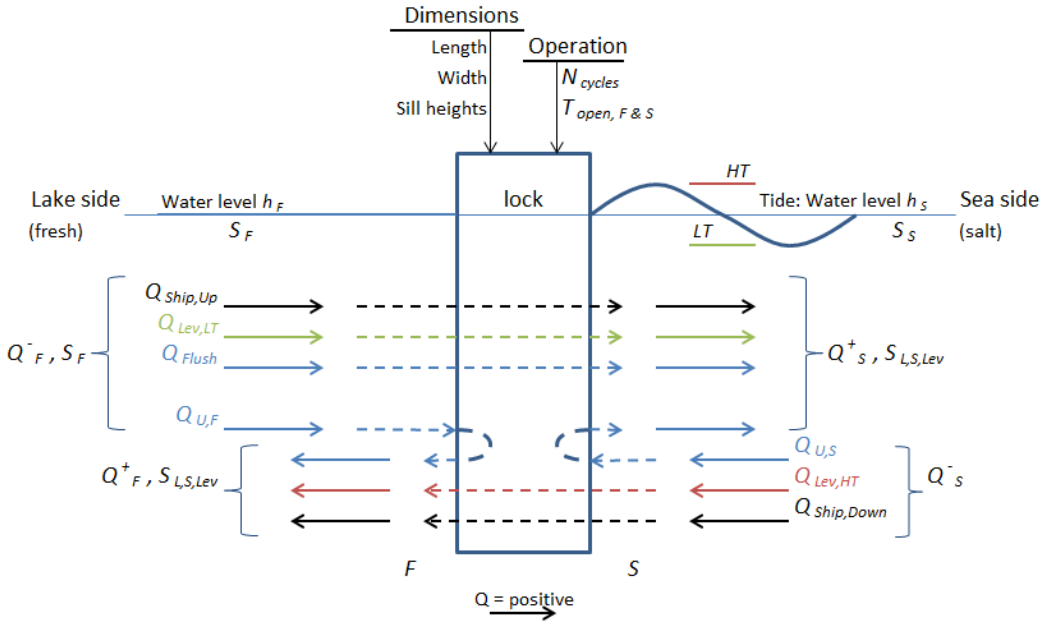

Fig. 1: *Schematic overview of the model concept: discharges going in and out on both sides of the lock, with their corresponding salinities.*

4.2.1 Processes in the locking cycle

4.2.1.1 Leveling

The locking of ships is in essence about overcoming a difference in water level. By letting a ship moore temporarily in a lock chamber, and by changing the water level in this lock chamber, the water level difference can be bridged. This process is called leveling. Raising the water level is done by letting water from the high side (‘filling’), and lowering the water level is done by letting out water to the low side (‘emptying’).

4.2.1.2 Lock exchange

Where there is a difference in salinity - and with that a difference in density - between both sides of the lock, a current will start to develop when the doors on either end are opened. This current is called a density current, and the phenomenon of this current exchanging the salt water in the lock chamber with fresh water (or vice versa) is called ‘lock exchange’. The less dense fresh water will start to float on top of the denser salt water, and move to the salt side. After reflection of the density current on the closed doors, the process continuous until just about the entire lock volume has been exchanged or until the doors are closed.

4.2.1.3 Locking operation

The locking operation concerns the opening and closing of doors on one side, leveling, the opening and closing of the doors on the other side, and leveling back again. When the doors open, ships will leave the lock chamber, before new ones going the opposite direction enter the lock chamber and the doors close again. The discharge through the lock due to leveling is determined by the surface area of the lock chamber, the water level difference, and the number of locking cycles per unit of time. For the lock exchange process, it is the time that the doors are open that matters. The time that the doors are open determines whether the density current partially or fully exchanges the water in the lock chamber.

4.2.1.4 Shipping

The presence of ships in the locking cycle influences the lock exchange in two ways:

1. When a ship enters a lock chamber, water is pushed out of said lock chamber. The amount of water that leaves the lock is equal to the water displacement of the ship. Conversely, when ships exit the lock chamber, water will flow from the approach harbor into the lock chamber to fill the 'hole' left by the ships.
2. The upwards leveling of a lock chamber means that water comes in from the high side. In case of a lock between salt- and fresh water, it is likely that the water that enters has a different salinity than the water inside the lock chamber. At the end of leveling the lock chamber will therefore have a new average salinity. When determining this average salinity we need to take into account that, when ships are present in the lock, there is less water inside the lock chamber.

The presence of ships inside the lock chamber does not have influence on the amount of water that is needed for leveling.

In the formulation of transports through the lock it is not about the individual but about the total water displacement of the ships per cycle. This value can differ for both direction, upstream and downstream. Do note that these two values do not have to be equal to each other. For example, when through a certain lock more cargo is imported than exported, this will be represented accordingly in the water displacements in both directions. With that, also a net discharge through the lock can arise.

4.2.1.5 Measures to prevent salt intrusion

To reduce the salt intrusion through shipping locks, a number of measures are available.

Bubble screens

Bubble screen in the lock heads reduce the velocity of the density current while the doors are open. It can therefore be an effective measure to reduce the salt intrusion, but the reduction also depends on limiting the amount of time the doors are open.

Flushing through the lock chamber

If the water level on the salt side is lower than that on the fresh side, the salt intrusion can be reduced by flushing the lock chamber with fresh water. When the lock opens to the fresh side, the water inside the lock chamber will have a lower salinity. This causes the density current velocity to drop, and also reduces the maximum amount of salt that can be transported due to lock exchange. When flushing with doors open, the flushing discharge with also reduce the velocity of the density current by means of superposition of velocities. Note that the same principle of flushing the lock can be applied when the water level on the salt side is higher, but pumps will be needed to realize the desired flushing discharge.

4.2.2 Conventions

For the positive direction of flows the dominant flow direction of the river or delta is chosen, i.e. downstream, towards the sea, from fresh to salt. This is in line with the convention of other software and model schematizations. Due to this choice, salt intrusion is a transport of salt in the negative direction.

This convention is also used in the figures in this documentation: a positive discharge means flow from left to right, with the upstream side on the left and the sea/salt side on the right.

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Subscripts to denote the lock chamber, the fresh side, and the salt side are respectively L, F, and S.

4.2.3 Phases of the locking cycle

In the figure below the different phases of the locking cycle are displayed and named. Because the direction of the leveling depends on whether the water level on the salt or fresh side is higher, there is a high water and low water state.

The water levels (h) on each side of the lock are defined as h_F for the water level on the fresh side, and h_S for the water level on the salt side. From this the definition of the high and low water state follows:

- when $h_S < h_F$ the state is LW
- when $h_S \geq h_F$ the state is HW

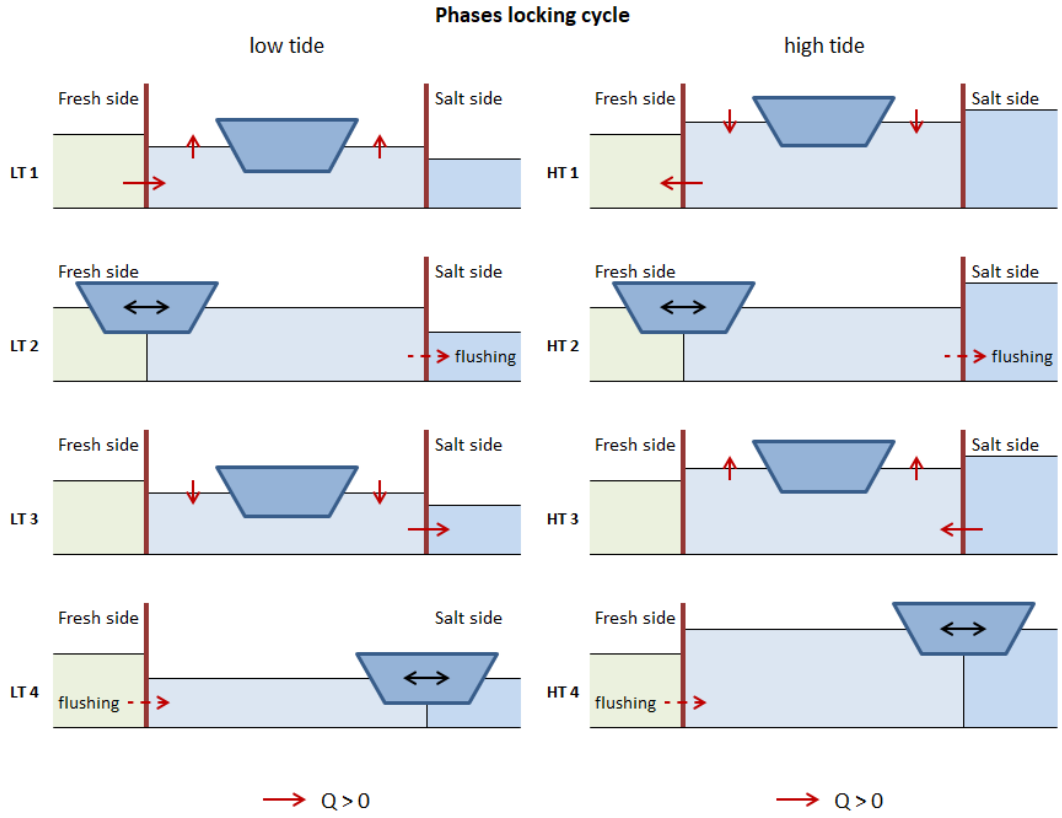

Fig. 2: *The phases of the locking cycle*

In this figure the positive direction is shown for the discharge (Q), but the same convention holds for the transported volume (V) and transported salt mass (M).

4.2.4 Physical quantities

The transports through a lock are determined by four categories of physical quantities:

- The boundary conditions on either side of the lock
- The geometry of the lock
- The operation of the lock
- The dimensions of the ship(s)

The calculated transports are expressed in terms of a transported salt mass per unit of time (or locking cycle), determined by the transported volumes and their corresponding salinities.

4.2.4.1 Boundary conditions

The boundary conditions on either side of the lock, the fresh side and the salt side, consist of a water level with a corresponding salinity or density. In stand-alone operation, these boundary conditions are prescribed by the user. When part of a larger (far-field) model, said model will prescribe the boundary conditions to the D-SLE.

h: The water levels on each side of the lock in [mDAT]

Suffix: L, F, and S for the lock, fresh side and salt side.

S: Salinity in [kg/m^3]

Suffix: L, F, and S for the lock, fresh side and salt side.

Second suffix for S_L:

F: direction after closing the door on the fresh side

S: direction after closing the door on the salt side

Third suffix for S_L or S_S:

Lev: after leveling, that follows on closing the door on the other side

$\overline{\rho}$: The average density of the water on each side of the lock head in [kg/m^3]

These values are generally available from a far-field model. In stand-alone usage, the density is calculated from the salinity using the UNESCO-formulation.

$\overline{\rho}_{FS}$: The average density of the water on the fresh and salt side in [kg/m^3]

These values are generally available from a far-field model. In stand-alone usage, the density is calculated from the salinity using the UNESCO-formulation.

4.2.4.2 Geometry

The general geometric parameters of the lock are:

L_L: length of the lock chamber in [m]

W_L: width of the lock chamber in [m]

z_L: bottom depth of the lock chamber in [mDAT]

From these follow:

H: water level over the bottom of the lock chamber or lock head in [m].

$$\begin{aligned} H_F &= h_F - z_L \\ H_S &= h_S - z_L \end{aligned} \tag{4.1}$$

V: the volume of the lock chamber in [m^3] at a certain water level

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$$V_{L,F} = L_L W_L H_F$$
$$V_{L,S} = L_L W_L H_S \quad (4.2)$$

Difference in the lock bottom layout inside and outside the lock chamber, combined with the possible presence of sills in the lock heads, will influence the lock exchange. For the correct calculation thereof, additional parameters are necessary. That is, it is necessary to define _effective_ values of length, depth and volume. The effective quantities are defined in the following equations.

If the lock bottom is equal throughout and there are no sills in the lock heads, it holds that:

$$L_{L,eff} = L_L \quad (4.3)$$

and

$$H_{F,eff} = H_F$$
$$H_{S,eff} = H_S \quad (4.4)$$

and

$$V_{L,F,eff} = V_{L,F}$$
$$V_{L,S,eff} = V_{L,S} \quad (4.5)$$

4.2.4.3 Operation

T_{in-use}: hours per day that the lock is operational [hour]

This is a constant with a value of 24 hours.

N_{cycles}: locking frequency [-]

The number of locking cycles (back and forth) per day.

T_{door}: time needed to move (open or close) the doors [min]

T_{level}: the average time needed to level the lock [min]

Research has shown that a variation in locking frequency over the day or week influences the salt intrusion significantly. To take this effect into account, two additional parameters are introduced:

c_{dot}: a calibration coefficient as a factor on the door-open time [-]

Default value is 1 (conservative); the range is $[0, 1]$

$C_{F/Avg}$: a symmetry coefficient indicating whether the doors are open equally long on both sides [-]

Default is 1 (equally long). Range is 0 (door on fresh side effectively never open) to 2 (door on salt side effectively never open).

From these parameters follow:

T_{cycle}: the average time for a complete locking cycle [s]

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$$T_{cycle} = \frac{T_{in-use} \cdot 60 \cdot 60}{N_{cycles}} \tag{4.6}$$

$T_{open,avg}$: the average door-open time [s]

$$T_{open,avg} = \frac{1}{2}T_{cycle} - \left(T_{level} + \frac{2}{2}T_{door}\right) \cdot 60 \tag{4.7}$$

Do note that for the calculation of the door-open time we subtract twice half the time it takes to open- or close the door. That means that effectively we assume that the lock-exchange process starts and ends when the doors are opened/closed halfway.

T_{open}: the representative door-open time [s]

$$T_{open} = c_{dot}T_{open,avg} \tag{4.8}$$

$T_{open,F}$ and $T_{open,S}$: the representative door-open times on the fresh and salt side [s]

$$\begin{aligned} T_{open,F} &= c_{F/Avg}T_{open} \\ T_{open,S} &= \left(2 - c_{F/Avg}\right)T_{open} \end{aligned} \tag{4.9}$$

4.2.4.4 Transports

M The amount of transported salt [kg] per locking phase (over a certain head)

first suffix: F, and S for the lock head on the fresh side or salt side.

second suffix: $LT1$ - $LT4$: phase of the locking cycle, simplified to just *1-4* if the formula is equal for both tidal phases.

V a volume of water with salt that is moved between lock and approach harbor [m^3]

suffixes:

Lev: due to leveling

followed by either *LT* or *HT*, depending on the direction of the head difference over the lock

U: due to lock exchange

followed by F, and S for fresh side or salt side

$Ship$: the total water displacement of the ships

Up: For ships moving in upstream direction, i.e. from salt to fresh side

Down: For ships moving in downstream direction, i.e. from fresh to salt side

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$Flush$: Due to a flushing discharge through the locking chamber

followed by either *LT* or *HT*, depending on the direction of the head difference over the lock

4.2.5 Calculation of the transported volumes

4.2.5.1 Leveling volume

The leveling volume plays a.o. a role in filling the lock chamber. Note that when filling the lock chamber, the salinity in the lock chamber changes. When emptying (i.e. leveling to the side with lower level), the salinity in the lock does not change.

Because the expression for filling and emptying are different, the formulas are separated. In addition, it is convenient to have different identifiers for both tidal phases.

$$LT : V_{level,LT} = L_L W_L \left(h_F - h_S\right), V_{level,HT} = 0 \tag{4.10}$$

$$HT : V_{level,LT} = 0, V_{level,HT} = L_L W_L \left(h_S - h_F\right) \tag{4.11}$$

4.2.5.2 Lock exchange

The lock exchange is often the most import process for lock intrusion through shipping locks. The process of lock exchange in time can be approximated with a hyperbolic tangent function. With that, the exchange volume $U(= V_U/V_K)$, slowly goes to 1 when the doors stay open for a long period of time.

$$V_U = V_L U = V_L \tanh\left(\frac{T_{open}}{T_{LE}}\right) \tag{4.12}$$

The door-open time T_{open} is in this expression compared to the (theoretical) time it takes for the density current to travel twice the length of the lock chamber.

The (initial) velocity of the density current c_i is determined by the relative density difference $\Delta\rho/\overline{\rho}$ and the water level in the respective head H

$$c_i = \frac{1}{2}\sqrt{g'H} = \frac{1}{2}\sqrt{g\frac{\Delta\rho}{\overline{\rho}}H} \approx \frac{1}{2}\sqrt{g0.8\frac{\Delta S}{\overline{\rho}_{FS}}H} \tag{4.13}$$

The difference in density can be approximated as 0.8 times the difference in salinity (in kg/m^3) between the lock and the approach harbor. For $\overline{\rho}$ a value could be deduced from both sides of the lock head at time of opening. Using a fixed value based on the boundary conditions (the average density over the lock $\overline{\rho}_{FS}$) introduces only a small approximation error.

With this density current velocity, T_{LE} can be defined as:

$$T_{LE} = \frac{2L}{c_i} = \frac{4L}{\sqrt{g\frac{0.8\Delta S}{\overline{\rho}_{FS}}H}} \tag{4.14}$$

The presence of sills and levels difference on the bottom of the lock chamber can influence the lock exchange. In this case, the values for the length, volume and water level depth will need to be adjusted.

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4.2.5.3 Bubble screens

The effectiveness of a bubble screen is often expressed as a factor on the velocity of the density current η. This density-current factor is a number in the interval [0, 1], the more effective a bubble screen the lower this value is (with a limit of about 0.2 - 0.25). With the velocity of the density current decreasing, the time it takes for a complete lock exchange increases. The factor can then be easily introduced in equation (4.12) describing the amount of volume exchanged due to lock exchange:

$$V_U = V_L U = V_L \tanh\left(\frac{\eta T_{open}}{T_{LE}}\right) \tag{4.15}$$

Note

This way of introducing η is elegant, but does imply that the only the velocity of the density current is changed, and e.g. the salinity of the density current is not. In reality the bubble screen will cause a lot of mixing to occur, and therewith the salinities of lock exchange to change.

4.2.6 Flushing discharge

A flushing discharge always goes from the fresh to the salt side. Such a discharge would generally only be possible in case of low-tide. In the high-tide case, a pump would be needed, and therefore the flushing discharge at high tide is often zero in practice. From an operational standpoint, there is a certain maximum instantaneous discharge. This is the discharge that is acceptable for the safe and speedy entry and exit of ships from the lock chamber. This momentaneous value (to be distinguished from the cycle-averaged discharge) is input by the user, with separate values for LT and HT.

$$LT : Q_{flush} = Q_{flush,LT} \tag{4.16}$$

$$HT : Q_{flush} = Q_{flush,HT} \tag{4.17}$$

In many cases there is only a discharge when either lock head is open. It is also possible to flush with both lock heads closed, but the leveling system still open. For now, we will assume the latter does not happen. That assumption then leads to the following equation for the flushed volume:

$$V_{flush} = Q_{flush}\left(T_{open,F} + T_{open,S}\right) \tag{4.18}$$

In practice, flushing is temporarily stopped when ships are sailing in from the fresh side to let them safely moor. This distinction cannot be made in the D-SLE, so flushing will happen for the entire door-open time.

The flushing discharge interacts with the density current and ships. For now, we will neglect the interaction of the flushing discharge and density current with the ships. In other words, in the discussion below, we will assume that the lock chamber does not contain any ships.

Generally we can assume a simple superposition of velocities when considering the interaction between flushing and lock exchange. This has consequences for the maximum exchangeable volume by the density current, which will discussed below in more detail using four scenario's. These scenario's differ in the magnitude of the flushing velocity (relative to the velocity of the density current):

1. No flushing discharge
2. Velocity of the flushing discharge is lower than that of the density current: $v_{flush} = 0.5 \cdot c_i$
3. Velocity of the flushing discharge is equal to that of the density current: $v_{flush} = c_i$
4. Velocity of the flushing discharge is larger than that of the density current: $v_{flush} = 1.5 \cdot c_i$

For every scenario we consider the entering (density) current, the reflecting, and the steady state condition at (infinitely) long door-open times.

Because the interaction between the flushing discharge and density current differs for the fresh side and salt side, they are discussed separately.

4.2.6.1 Flushing fresh side

Entering current

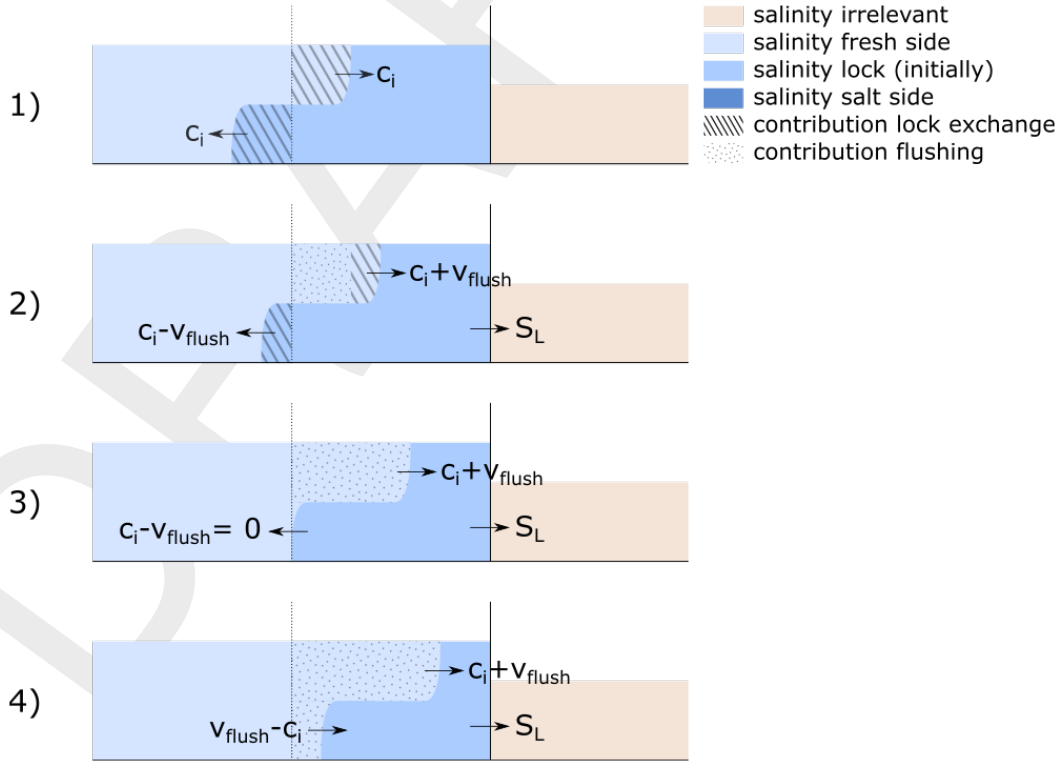

Fig. 3: *Schematic overview of the entering density current as a function of the flushing discharge*

In Scenario 1 the lock exchange is displayed for when there is no flushing discharge, as described in Section 4.2.5.2. The water that is exchange between the lock and the fresh approach harbor can be fully attributed to the density current.

In Scenario 2 is visible what happens when there is a flushing discharge with a velocity lower than that of the density current. The water from the lock chamber that enters the approach harbor can only get there because of the density current / lock exchange process. There is an equally large contribution of lock exchange in the lock chamber itself, but another part of the fresh water that has entered is due to the flushing discharge. In case of a flushing velocity of $0.5 \cdot c_i$ the ratio is 2/3 flushing discharge, and 1/3 lock exchange.

In Scenario 3 and 4 is visible what happens when the flushing velocity equals or exceeds the velocity of the density current. In these cases, the density current cannot exit the lock cham-

ber, and as such we can say that no lock exchange has happened. The volume-averaged salinity of the lock chamber dropping can then be entirely attributed to the flushing discharge.

Reflecting current

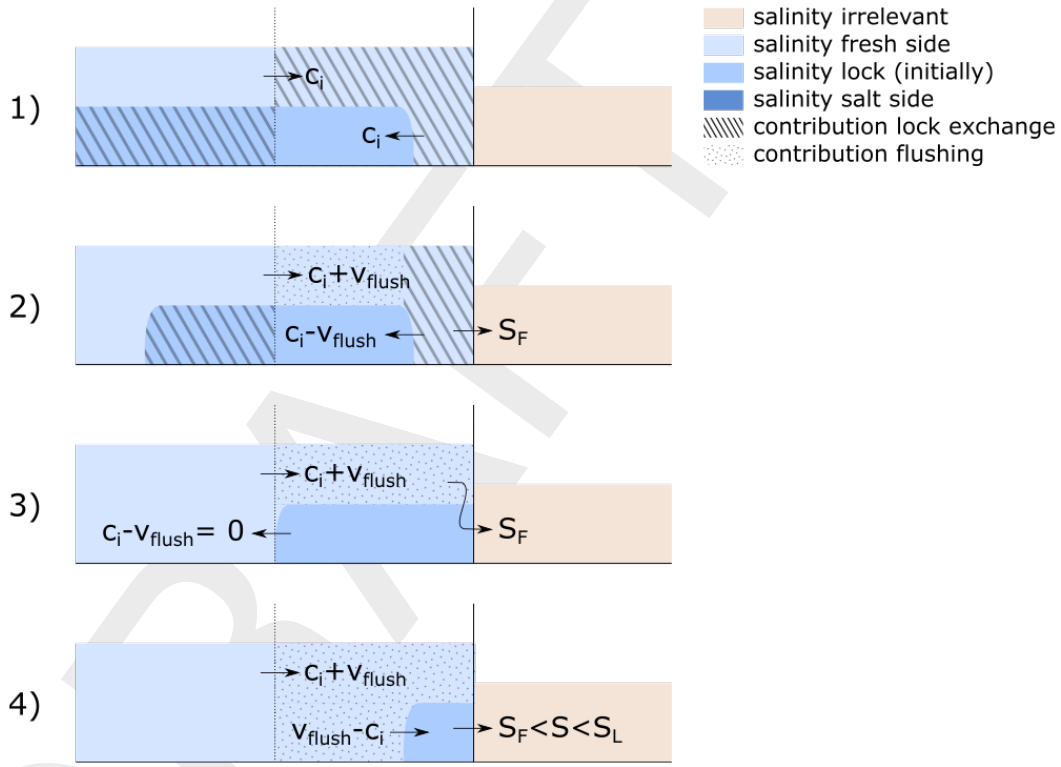

Fig. 4: *Schematic overview of the reflecting density current as a function of the flushing discharge*

When there is flushing discharge as in Scenario 1, the pace of the fresh water displacing salt water in the lock chamber after reflection is equal to that of an entering current. This holds when we assume velocities as shown in the figure above. In Section 4.2.5.2 a hyperbolic-tangent approach was used, which implies that the velocity of the density current slowly (but steadily) decreases.

In Scenario 2 is visible what happens when there would a flushing discharge. For an entering density current the water that goes to the salt side still has a salinity of S_L. That has now turned into water with salinity S_F This means that the pace of the lock chamber's salinity dropping in this phase scales with the velocity of the exiting density current, because all incoming flushing discharge with salinity S_F will pass right through the lock chamber and exit to the salt side. Contrary to Scenario 1, that means that the pace of the lock chamber's salinity dropping suddenly changes when the density current reflects. After reflection, the lock chamber becomes fresh slower than for an entering density current.

For Scenario 3 we extrapolate from Scenario 2, and therefore assume that the water leaving the lock chamber on the salt-side head has a salinity of that of the fresh side. For Scenario 4, a mixture of fresh water and water from the lock chamber exits to the salt side. As such, the salinity of the water going to the salt side is somewhere between these two.

Final (steady) state

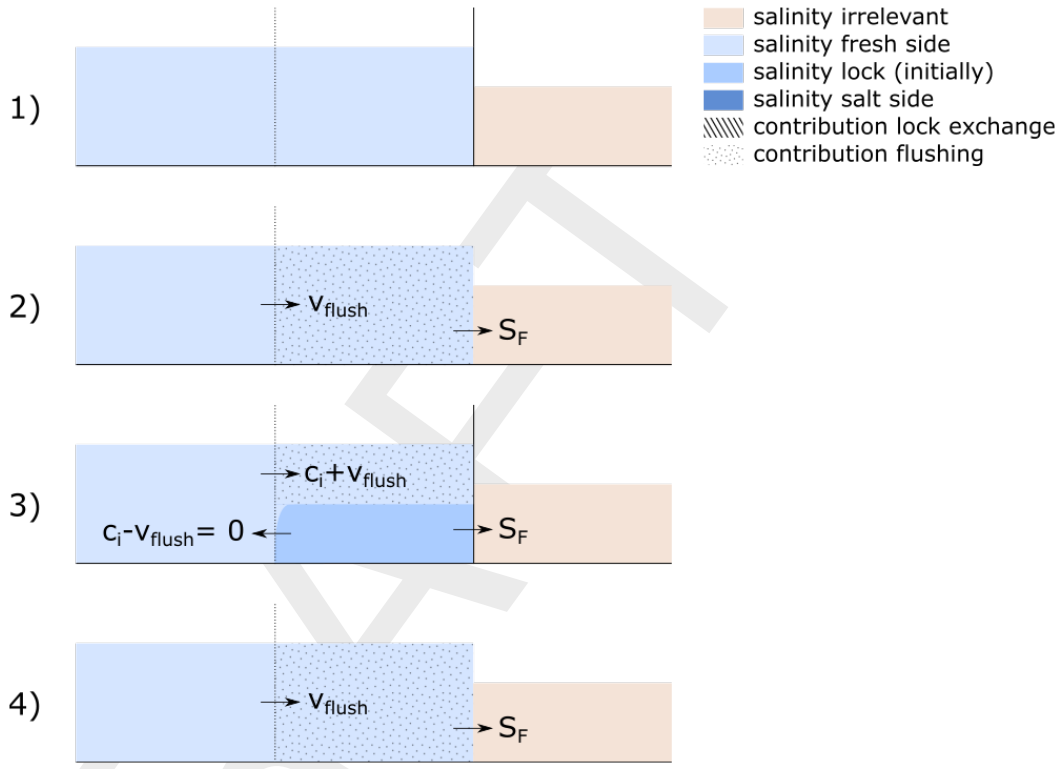

Fig. 5: *Schematic overview of the final state of the lock chamber as a function of the flushing discharge*

In the hypothetical case that the door is opened infinitely long, the final state in the lock chamber is often a fully fresh one. Only for Scenario 3 there would still be a salt bottom layer present. This is because, based on superposition of velocities alone, this layer never moves. In reality, mixing on the boundary layer between salt and fresh will slowly erode this bottom layer, such that also in this case a fully fresh lock chamber results.

Simplifications and formulation

In previous sections was discussed how the entering and reflecting density current behave if we assume a superposition of velocities. In Section 4.2.5.2 the lock exchange with flushing discharge is already written down in mathematical relations. Whereas a single formulation could cover all defined scenario's for the entering density current, that is no longer possible when also having to take the reflecting density current or final state into account. There would be an abrupt change in the pace with which the lock chamber's salinity drops, and also an abrupt change in the salinity of the flushing water going to the salt side. Furthermore, in the above discussion mixing/erosion has not been taken into account, even though those would occur in reality.

To come to a simple formulation, we make the following assumptions:

- ◇ The final state is always a fully fresh lock chamber (like in Scenario 1, 2 and 4). With this assumption we are closer to reality than would be the case based on superposition of velocities alone.
- ◇ The initial pace of salinity change in the lock (for an entering density current) scales with the ratio with the flushing velocity. This pace is kept even when the density current reflects, and slowly goes to zero with a hyperbolic tangent just like in Section 4.2.5.2.

◇ The pace of salinity change due to the flushing discharge is constant. In other words, the flushing water that enters the lock has a salinity of that of the fresh side, and the flushing water that exits has a salinity equal to that of the lock chamber when the doors opened. As soon as the lock is entirely fresh, flushing no longer has any effect on the salinity of the lock chamber, and as such we assume that the salinity of the water going to the salt side then switches to being equal to that of the fresh side (and equal to that of the lock chamber in that moment).

Written in equations, we see that the fraction of lock exchange in Scenario 2 scales linearly with the ratio of the flushing velocity to the velocity of the density current, until the situation of Scenario 3 is reached:

$$f_{LE,flush} = max\left(\frac{c_i - v_{flush}}{c_i}, 0\right) \tag{4.19}$$

This leads to the following equation for the exchanged volume due to lock exchange (with V_U as defined in Section 4.2.5.2):

$$V_{U,F} = f_{LE,flush} V_U \tag{4.20}$$

With these simplifications the lock becomes fresher quicker than in reality, but there is also less salt going to the fresh side. How conservative or optimistic this formulation then is (and with that the salt/fresh load), is unknown. This uncertainty is an important point of attention when interpreting the calculated salt and fresh loads.

For Scenario 2, 3 and 4 it holds that flushing displaces the following volume:

$$V_{flush} = Q_{flush} T_{open,F} \tag{4.21}$$

The salinity of the flushing discharge is always S_F over the fresh-side head. The salinity of the flushing discharge over the salt-side head is initially S_L, switching to S_F as soon as the lock is fully fresh. In Scenario 3 and 4, where contrary to Scenario 1 and 2 there is no contribution of the lock exchange to the salinity decrease, this switch happens as soon as V_{flush} is equal to V_L.

4.2.6.2 Flushing salt side

When flushing with the door on the salt side opened, fresh water is entering the lock chamber from the fresh side. Two extremes of that situation are shown in the figure below. In reality, the distribution of the fresh water will be somewhere inbetween the extremes shown. In addition, the boundary between the fresh water and the saltier water in the lock chamber will not be as sharp due to mixing. As such, the water that goes to the the salt side will become fresh before the lock exchange process is done.

In the discussion of the entering and reflecting density current below we neglect the effect the dilution of the lock chamber has on the velocity of said density current.

Entering current

In Scenario 1 in the figure above the situation is shown for a density current with no flushing discharge. The water that is exchanged between the lock chamber and the salt approach harbor can be fully attributed to the density current, traversing with velocity c_i.

In Scenario 2 is visible what happens when one flushes with a velocity lower than that of the density current. The salty approach water that moves across the opened door into the lock chamber can only get there due to the lock exchange process / density current. An equal

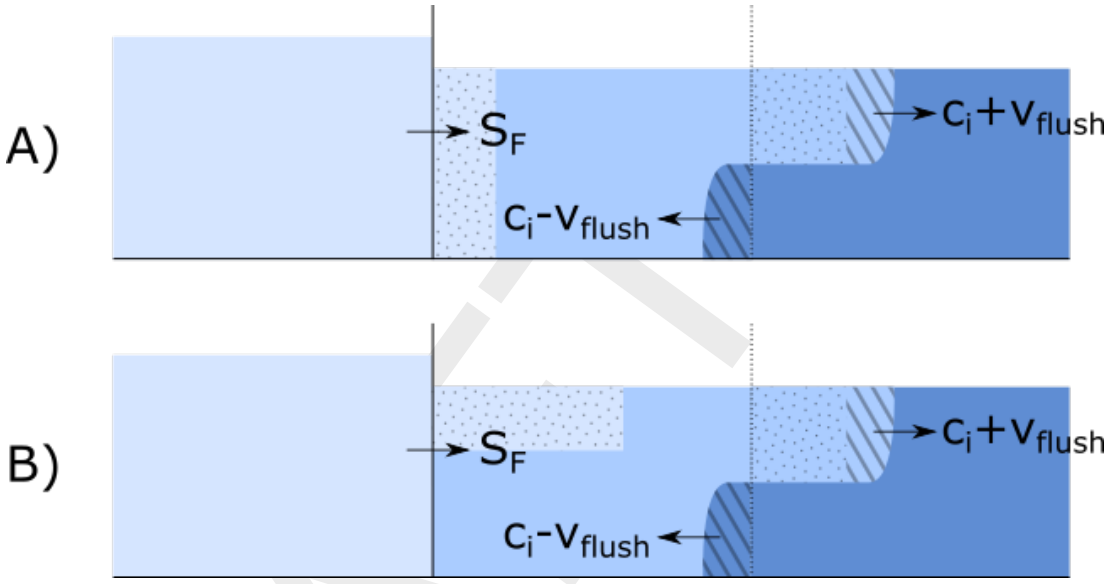

Fig. 6: *Schematic overview of fresh flushing water entering the lock when salt-side door is open*

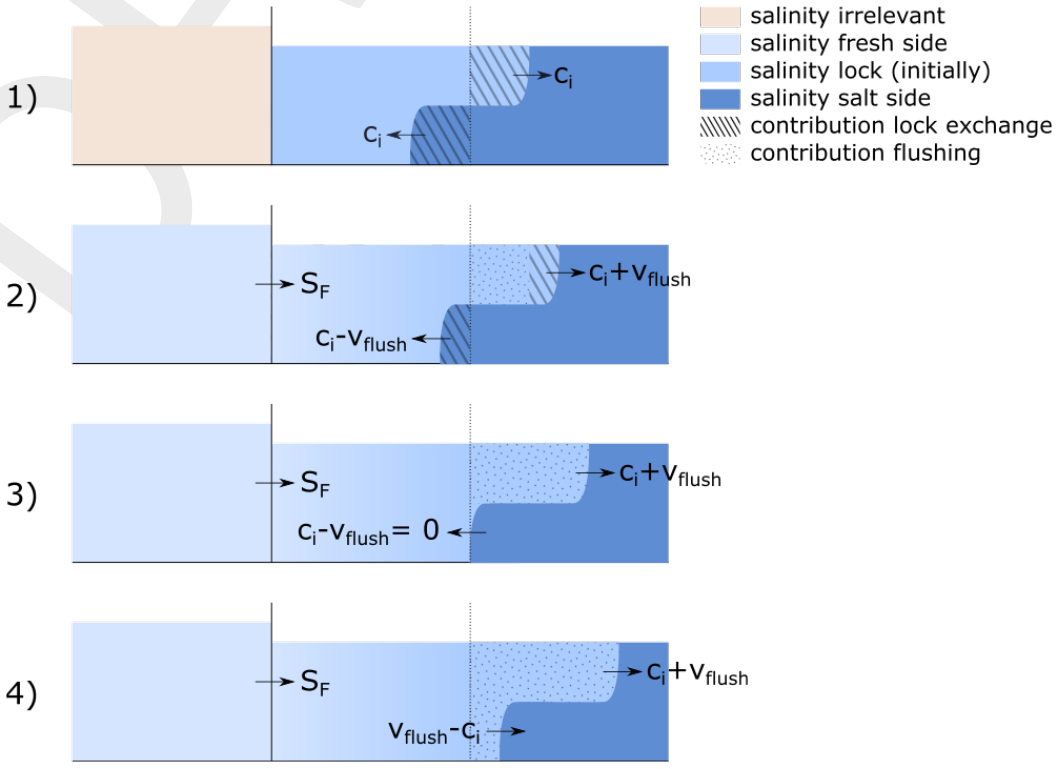

Fig. 7: *Schematic overview of the entering density current as a function of the flushing discharge*

amount of water from the lock chamber exits to the approach harbor by way of the density current. The remainder of the lock chamber water that exits the lock is due to the flushing discharge. An equal amount of fresh water enters the lock from the lake side through the closed doors. That means the salinity in the lock is both increasing (near the sea side) and decreasing (near the fresh side).

In Scenario 3 and 4 is visible what happens when the velocity of the flushing discharge equals or surpasses that of the density current. In this case, the density current is not able to enter the lock, and as such we can say that there is no lock exchange taking place. There is however a dilution of the lock chamber, which can be fully attributed to the flushing discharge.

Reflecting current

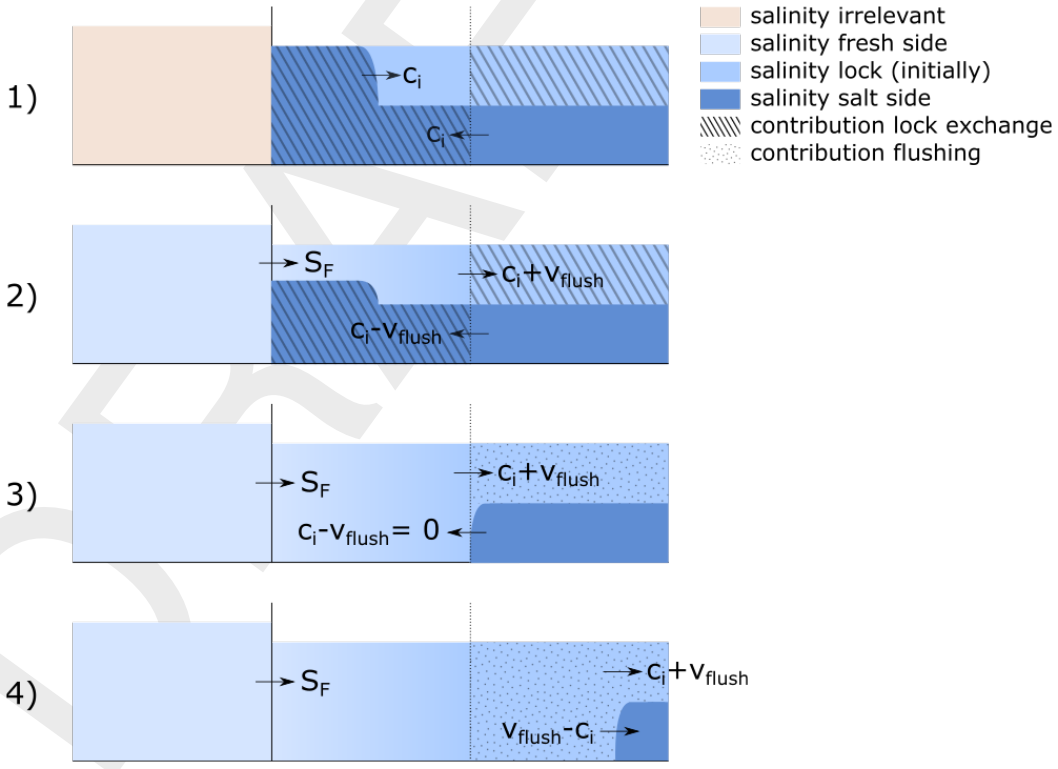

Fig. 8: *Schematic overview of the reflecting density current as a function of the flushing discharge*

When there is no flushing discharge, the pace of salinization of the lock chamber is equal to that of an entering current, if we assume the velocities as shown in the figure above. In Section 4.2.5.2 an approach with a hyperbolic tangent is described, which would mean that the pace of salinization would slowly but steadily drop.

In Scenario 2 is visible what happens when a flushing discharge is present. The salt wedge still enters with the same velocity, but exiting wedge (top layer) should exit more quickly because it cannot take up the full (half) height.

In Scenario 3 and 4 the density current does not enter the lock. In reality the density current will slowly start to enter the lock in Scenario 3, because the lock chamber is diluting and with that the driving density difference increases. The salinity of the water that leaves the lock to the salt approach harbor in this phase is likely somewhere between that of the initial salinity of the lock chamber, and that of the fresh side.

Final (steady) state

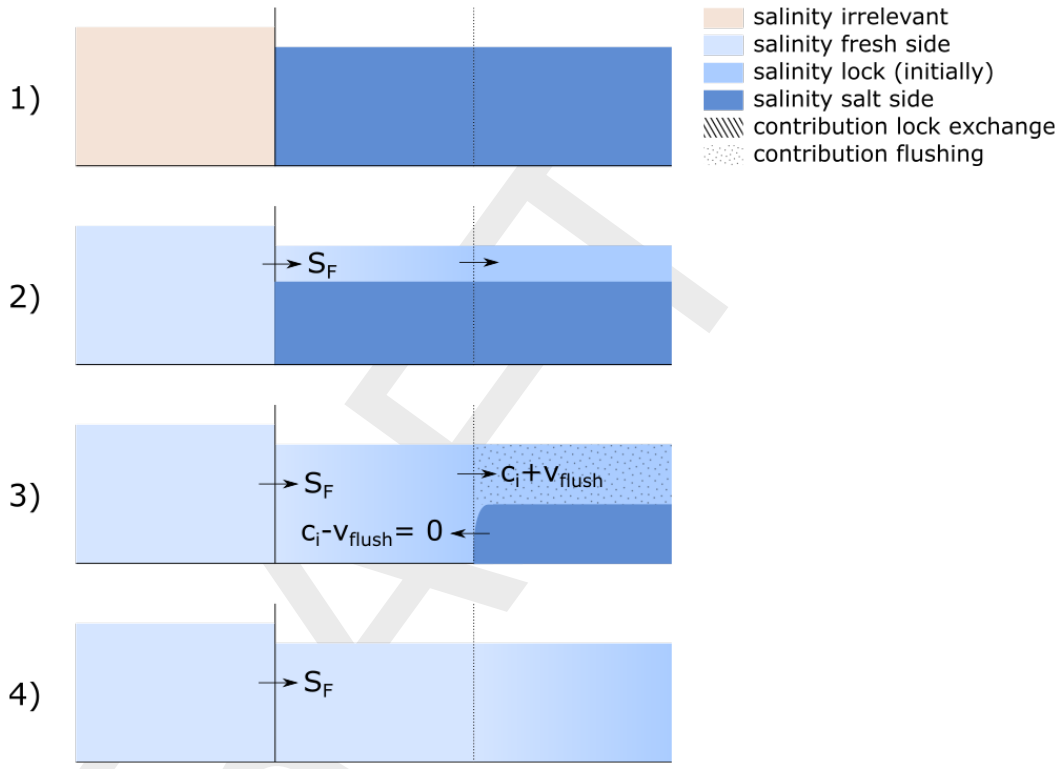

Fig. 9: *Schematic overview of the final state of the lock chamber as a function of the flushing discharge*

When the door on the sea side is open infinitely long, the equilibrium situation is dependent on the velocity of the flushing discharge.

In Scenario 1 the lock chamber will have acquired a salinity equal to that of the salt side.

In Scenario 2 a certain equilibrium between the driving salinity difference and flushing discharge is obtained. Shown in the figure above we assume a sharp interface between the salt bottom layer and the fresh layer of flushing discharge. In reality, instabilities on this interface will cause mixing, and this in turn will influence the lock exchange.

In Scenario 3 and 4 the lock chamber becomes fully fresh. A nuance is that the driving salinity difference does increase with the lock chamber diluting, and with that a density current might start to enter the lock chamber eventually anyway. That would then lead to an equilibrium state more equal to that of Scenario 2.

Simplifications and formulation

In previous sections was discussed how the entering and reflecting density current behave if we assume a superposition of velocities. In Section 4.2.5.2 the lock exchange with flushing discharge is already written down in mathematical relations. Contrary to the discussion of the fresh side, there is now a clear distinction between the final steady state in Scenario 1 and 2 (lock chamber fully or just partially salinized), and Scenario 3 and 4 (lock chamber diluted to salinity of fresh side). The formulation that is derived should therefore also make a distinction between these two.

Just like in the discussion for the fresh side, it is difficult to describe the transition from entering to reflecting density current. This is further complicated by the slow dilution of the lock

chamber with fresh water, where it is not known how and where this water mixes with that of the lock chamber (i.e. does the fresh water float to the top, or does the entire lock chamber dilute more uniformly).

To come to a simple formulation, we make the following assumptions:

- ◇ The height of the top layer that forms in Scenario 2 is a function of the density difference between the salt side and the fresh side, and the flushing discharge. The higher the flushing discharge the thicker this layer of fresh water in the lock chamber. The higher the density difference, the thinner this layer is.
- ◇ In Scenario 1 and 2 we use the behavior as discussed in Section 4.2.5.2, where the pace of the lock exchange steadily decreases. The initial velocity of the density current is $c_i - v_{flush}$, and the maximum volume that can be exchanged is only part of the volume of the lock chamber (as discussed in the previous assumption). That is, the maximum exchangeable volume is $V_L - V_{top-layer}$.
- ◇ In Scenario 3 and 4 the lock chamber the salt density current will never enter the lock chamber. The pace of dilution due to the flushing discharge is assumed constant. In other words, the water that enters the lock has a salinity of that of the fresh side, and the water that exits has a salinity equal to the initial (at time of opening of the doors) salinity of the lock chamber. As soon as the lock chamber has been fully diluted, the salinity of the water that exits switches to that of the fresh side (equal to the lock chamber at that point in time).

For Scenario 1 we can then use the formulation of Section 4.2.5.2 as-is, or the below formulation for Scenario 2 with the height of the top layer equal to zero. For Scenario 2 it holds that we can solve for the thickness of the top layer by rewriting (4.13), and setting c_i equal to the velocity of the water in the top layer $v_{top-layer}$.

$$H_{eq} = 0.5 \frac{\left(2 \cdot v_{top-layer}\right)^2 \cdot \overline{\rho}_{FS}}{g \cdot 0.8 \left(S_S - S_F\right)} \tag{4.22}$$

$$v_{top-layer} = \frac{Q_{flush}}{H_{eq} \cdot W_L} \tag{4.23}$$

To make the process of rewriting easier to understand, we merge all fixed terms into one constant:

$$C = \frac{\overline{\rho}_{FS}}{g \cdot 0.8 \left(S_S - S_F\right)} \tag{4.24}$$

We can then write H_{eq} as a function of itself:

$$H_{eq} = 2 \frac{Q_{flush}^2}{H_{eq}^2 W_L^2} \cdot C \tag{4.25}$$

The last step is to make this height explicit:

$$H_{eq} = \left(2 \cdot \frac{Q_{flush}^2}{W_L^2} \cdot C\right)^{\frac{1}{3}} \tag{4.26}$$

With that, the maximum volume that can be exchanged by the density current then is:

$$f_{LE,flush} = \frac{H_S - H_{eq}}{H_S} \tag{4.27}$$

The time T_{LE} that it takes to exchange this volume is defined as follows:

$$T_{LE,S} = \frac{2 \cdot f_{LE,flush} \cdot L_L}{\eta c_i - v_{flush}} \tag{4.28}$$

This leads to the following equation for the exchanged volume by the density current:

$$V_{U,S} = f_{LE,flush} V_{L,S} \tanh\left(\frac{T_{open}}{T_{LE,S}}\right) \tag{4.29}$$

For Scenario 2 - 4 it holds that the flushing discharge displaces the following volume:

$$V_{flush} = Q_{flush} T_{open,S} \tag{4.30}$$

The salinity of this discharge is always S_F over the fresh-side head, i.e. when it enters the lock chamber. For the sea-side lock head, the salinity is initially S_L, switching to S_F as soon as the lock has been fully diluted. In Scenario 3 and 4, where contrary to Scenario 1 and 2 there is no salinization of the lock chamber, this switch in salinity happens as soon as V_{flush} is equal to V_L.

4.2.7 Overview of the input

Boundary conditions (only in stand-alone version):

h_F, h_S, S_F, S_S, T_F, T_S

Of these, especially h_S will be a time-dependent variable to study the influence of a tide.

Geometry (not taking into account sills and an uneven lock bottom):

Constant in time: L_L, W_L, z_L

Operation and shipping information:

N_cycles, T_{door}, T_{level}, c_{dot}, $C_{F/Avg}$, $V_{Ship,Up}$, $V_{Ship,Down}$

Initially all values are constant in time. However, to describe fluctuations in the operation of the lock in time (depending on how busy it is), and to describe variation in the direction of the overall shipping traffic, N_cycles, $C_{F/Avg}$, $V_{Ship,Up}$, $V_{Ship,Down}$ should be time-dependent parameters.

Measures:

Constant in time: η, $Q_{flush,LT}$, $Q_{flush,HT}$

4.3 Equations per locking phase

Below we discuss, per locking phase, the equations for the mass transport of salt, expressed in terms of volumes with certain salinity. Eventually the transports over the entire locking cycle can then be determined by aggregating the transports per phase.

Because we assume cyclic operation of the lock, the initial condition of the lock (e.g. salinity) are equal to the conditions at the end of the cycle.

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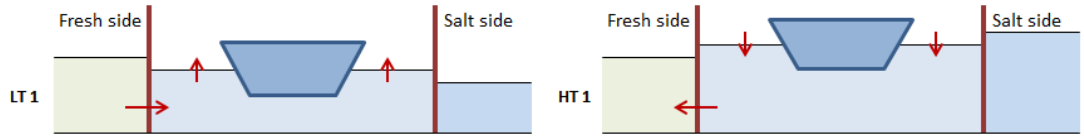

Fig. 10: *Schematic overview of leveling to the fresh side during low and high tide*

4.3.1 Phase 1: Leveling to fresh side

The leveling takes place on the fresh-side head. There are no transports over the sea-side head.

The salt transport due to leveling at low tide (LT) can be described as:

$$LT : M_{F,LT1} = V_{level,LT} S_F \tag{4.31}$$

Similarly for high tide:

$$HT : M_{F,HT1} = -V_{level,HT} S_{L,S} \tag{4.32}$$

By definition (see (4.10) and (4.11)) either $V_{level,LT}$ or $V_{level,HT}$ is zero, we can sum them up into one single equation:

$$M_{F,1} = V_{level,LT} S_F - V_{level,HT} S_{L,S} \tag{4.33}$$

When leveling at low tide, the average salinity of the water in lock chamber drops because fresh water is let in. To calculate this new salinity, we have to take into account the water displacement of ships present in the lock chamber:

$$LT : S_{L,S,Lev} = \frac{S_{L,S} \left(V_{L,S} - V_{Ship,Up} \right) + S_F V_{Lev,LT}}{V_{L,F} - V_{Ship,Up}} \tag{4.34}$$

In the situation around high tide, water is extracted from the lock chamber to lower the level, which does not change the salinity of the lock chamber:

$$HT : S_{L,F,Lev} = S_{L,S} \tag{4.35}$$

With this, we can write (4.33) as follows:

$$M_{F,1} = V_{level,LT} S_F - V_{level,HT} S_{L,S,Lev} \tag{4.36}$$

(The salinity in the lock chamber after Phase 1, $S_{L,S,Lev}$ can also be written as $S_{L,1}$.)

The phase-averaged discharges to and withdrawals from the fresh side are then as follows (note that there are no flows on the salt side):

◇ withdrawal from the fresh side, with the prevailing salinity S_F:

$$V^-_{F,1} = V_{Lev,LT} \tag{4.37}$$

$$Q^-_{F,1} = \frac{V^-_{F,1}}{T_{Lev}} \tag{4.38}$$

◇ discharge to the fresh side with salinity $S_{L,S}$:

$$V^+_{F,1} = V_{Lev,HT} \tag{4.39}$$

$$Q^+_{F,1} = \frac{V^+_{F,1}}{T_{Lev}} \tag{4.40}$$

4.3.2 Phase 2: Door open on fresh side

The figure below illustrates that in principle there are no differences between low tide and high tide. In case of flushing through the lock, there is also a transport over the sea-side head.

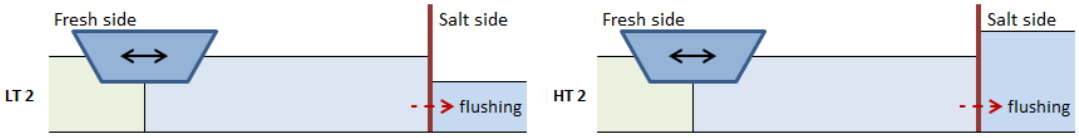

Fig. 11: *Schematic overview of flows when door is open on the fresh side during low and high tide*

While the doors are open on one side there are various processes that take place that contribute to the transport of salt over the opened lock head. These processes are:

1. Salt transport due to ships exiting the lock chamber
2. Salt transports due to the lock exchange (with or without flushing)
3. Salt transport due to ships entering the lock chamber

If the transports due to these processes are independently calculated before adding them up, there is a possibility of the salt transport being too high. This would result in a salinity in the lock chamber that is lower than the fresh side, or higher than the salt side. To prevent this from happening, Phase 2 has been divided into three subphases, corresponding to the list above. Each of these subphases leads to a new intermediate salinity of the lock chamber:

1: Salt transport due to ships exiting the lock

$$M_{F,2a} = V_{Ship,Up} S_F \tag{4.41}$$

$$S_{L,2a} = \frac{S_{L,S,Lev} \left(V_{L,F} - V_{Ship,Up} \right) + M_{F,2a}}{V_{L,F}} \tag{4.42}$$

2. Salt transport due to lock exchange (with or without flushing)

Contribution of lock exchange:

$$M_{F,2b,LE} = V_{U,F} S_F - V_{U,F} S_{L,2a} \tag{4.43}$$

With $V_{U,F}$ as determined in (4.20).

Contribution of flushing over fresh-side head:

$$V_{flush} = Q_{flush} T_{open,F} \tag{4.44}$$

$$M_{F,2b,flush} = V_{flush} S_F \tag{4.45}$$

Contribution of flushing over the salt-side head. When flushing for such a long time that the lock chamber's salinity reaches that of the fresh side, the salinity of the water going to the sea side changes accordingly:

$$V_{flush,max} = V_{L,F} - V_{U,F} \tag{4.46}$$

$$M_{S,2b,flush} = min\left(V_{flush}, V_{flush,max}\right) S_{L,2a} + max\left(V_{flush} - V_{flush,max}, 0\right) S_F \quad (4.47)$$

The new salinity at the end of this subphase then is:

$$S_{L,2b} = \frac{S_{L,2a} V_{L,F} + M_{F,2b,LE} + M_{F,2b,flush} - M_{Z,2b,flush}}{V_{L,F}} \quad (4.48)$$

3. Salt transport due to ships entering the lock

$$M_{F,2c} = -V_{Ship,Down} S_{L,2b} \quad (4.49)$$

4.3.3 Phase 2: Total transports

The total transport of salt over the fresh-side head in this Phase is the sum of the transports of each subphase:

$$M_{F,2} = M_{F,2a} + M_{F,2b,flush} + M_{F,2b,LE} + M_{F,2c} \quad (4.50)$$

In case of a non-zero flushing discharge, there is also a transport over the salt-side head:

$$M_{S,2} = M_{S,2b,flush} \quad (4.51)$$

The resulting salinity in the lock is then:

$$S_{L,F} = \frac{S_{L,S,Lev}\left(V_{L,F} - V_{Ship,Up}\right) + M_{M,2} - M_{S,2}}{\left(V_{L,F} - V_{Ship,Down}\right)} \quad (4.52)$$

(The salinity in the lock after Phase 2, $S_{L,F}$, can also be written as $S_{L,2}$.)

The phase-averaged discharges to and withdrawals from the fresh and salt side are then as follows:

◇ withdrawal from the fresh side, with the prevailing salinity S_F:

$$V^-_{F,2} = V_{Ship,Up} + V_{U,F} + V_{flush} \quad (4.53)$$

$$Q^-_{F,2} = \frac{V^-_{F,2}}{T_{open,F}} \quad (4.54)$$

◇ discharge to the fresh side with salinity $S^+_{F,2}$:

$$V^+_{F,2} = V_{Ship,Down} + V_{U,F} \quad (4.55)$$

$$Q^+_{F,2} = \frac{V^+_{F,2}}{T_{open,F}} \quad (4.56)$$

$$S^+_{F,2} = -\frac{M_{F,2} - V^-_{F,2} \cdot S_F}{V^+_{F,2}} \quad (4.57)$$

◇ there is no withdrawal from the salt side in this Phase
◇ discharge to the salt side with average salinity S^+_S

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$$V^{+}_{S,2} = Q_{flush} T_{open,F} \tag{4.58}$$

$$Q^{+}_{S,2} = Q_{flush} \tag{4.59}$$

$$S^{+}_{S,2} = \frac{M_{S,2}}{V^{+}_{S,2}} \tag{4.60}$$

4.3.4 Phase 3: Leveling to salt side

The leveling takes place on the sea-side head. There are no transports over the fresh-side head.

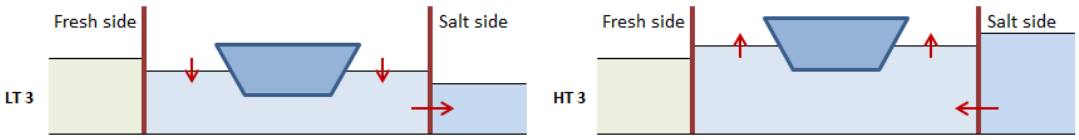

Fig. 12: *Schematic overview of leveling to the salt side during low and high tide*

Just like in Phase LT 1 and HT 1 it holds that by definition either $V_{level,LT}$ or $V_{level,HT}$ is zero. Therefore we can sum the equations for both tidal phases up into a single one:

$$M_{F,3} = V_{level,LT} S_{L,F} - V_{level,HT} S_S \tag{4.61}$$

In the situation around low tide, water is extracted from the lock chamber to lower the level, which does not change the salinity of the lock chamber:

$$LT : S_{L,F,Lev} = S_{L,F} \tag{4.62}$$

When leveling at high tide, the average salinity of the water in lock chamber rises because salt water is let in. To calculate this new salinity, we have to take into account the water displacement of ships present in the lock chamber:

$$HT : S_{L,F,Lev} = \frac{S_{L,F} \left(V_{L,F} - V_{Ship,Down} \right) + S_S V_{Lev,HT}}{V_{L,S} - V_{Ship,Down}} \tag{4.63}$$

With this, we can write (4.61) as follows:

$$M_{S,3} = V_{level,LT} S_{L,F,Lev} - V_{level,HT} S_S \tag{4.64}$$

(The salinity in the lock chamber after Phase 3, $S_{L,F,Lev}$ can also be written as $S_{L,3}$.)

The phase-averaged discharges to and withdrawals from the salt side are then as follows (note that there are no flows on the fresh side):

◇ withdrawal from the salt side, with the prevailing salinity S_S:

$$V^{-}_{S,3} = V_{Lev,HT} \tag{4.65}$$

$$Q^{-}_{S,3} = \frac{V^{-}_{S,3}}{T_{Lev}} \tag{4.66}$$

◇ discharge to the salt side with salinity $S_{L,F}$:

$$V_{S,3}^{+} = V_{Lev,LT} \tag{4.67}$$

$$Q_{S,3}^{+} = \frac{V_{S,3}^{+}}{T_{Lev}} \tag{4.68}$$

4.3.5 Phase 4: Door open on salt side

The figure below illustrates that in principle there are no differences between low tide and high tide. In case of flushing through the lock, there is also a transport over the fresh-side head.

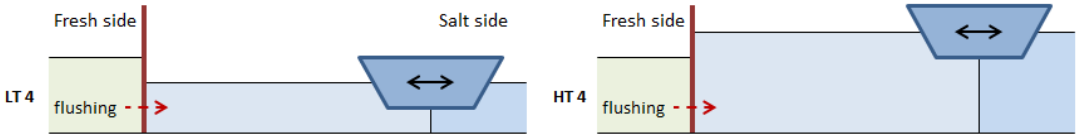

Fig. 13: *Schematic overview of flows when door is open on the salt side during low and high tide*

While the doors are open on one side there are various processes that take place that contribute to the transport of salt over the opened lock head. These processes are:

1. Salt transport due to ships exiting the lock chamber
2. Salt transports due to the lock exchange (with or without flushing)
3. Salt transport due to ships entering the lock chamber

If the transports due to these processes are independently calculated before adding them up, there is a possibility of the salt transport being too high. This would result in a salinity in the lock chamber that is lower than the fresh side, or higher than the salt side. To prevent this from happening, Phase 4 (just like Phase 2) has been divided into three subphases, corresponding to the list above. Each of these subphases leads to a new intermediate salinity of the lock chamber:

1: Salt transport due to ships exiting the lock

$$M_{S,4a} = -V_{Ship,Down} S_S \tag{4.69}$$

$$S_{L,4a} = \frac{S_{L,F,Lev}\left(V_{L,S} - V_{Ship,Down}\right) + M_{S,4a}}{V_{L,S}} \tag{4.70}$$

2. Salt transport due to lock exchange (with or without flushing)

Contribution of lock exchange:

$$M_{S,4b,LE} = V_{U,S} S_{L,4a} - V_{U,S} S_S \tag{4.71}$$

With $V_{U,S}$ as determined in (4.29).

Contribution of flushing over fresh-side head:

$$V_{flush} = Q_{flush} T_{open,S} \tag{4.72}$$

$$M_{F,4b,flush} = V_{flush} S_F \tag{4.73}$$

Contribution of flushing over the salt-side head. When flushing for a long, an equilibrium situation arises as described in Section 4.2.6.2. Furthermore, the salinity of the flushing discharge going to the salt side changes from that of the (initial salinity of the) lock chamber to that of the fresh side.

$$V_{flush,max} = V_{L,S} - V_{U,S} \tag{4.74}$$

$$M_{S,4b,flush} = min\left(V_{flush}, V_{flush,max}\right) S_{L,4a} + max\left(V_{flush} - V_{flush,max}, 0\right) S_F \tag{4.75}$$

The new salinity at the end of this subphase then is:

$$S_{L,4b} = \frac{S_{L,4a} V_{L,S} + M_{S,4b,LE} + M_{F,4b,flush} - M_{Z,4b,flush}}{V_{L,S}} \tag{4.76}$$

3. Salt transport due to ships entering the lock

$$M_{S,4c} = V_{Ship,Up} S_{L,4b} \tag{4.77}$$

4.3.6 Phase 4: Total transports

The total transport of salt over the salt-side head in this Phase is the sum of the transports of each subphase:

$$M_{S,4} = M_{S,4a} + M_{S,4b,flush} + M_{S,4b,LE} + M_{S,4c} \tag{4.78}$$

In case of a non-zero flushing discharge, there is also a transport over the fresh-side head:

$$M_{F,4} = M_{F,4b,flush} \tag{4.79}$$

The resulting salinity in the lock is then:

$$S_{L,S} = \frac{S_{L,F,Lev}\left(V_{L,S} - V_{Ship,Down}\right) + M_{M,4} - M_{S,4}}{\left(V_{L,S} - V_{Ship,Up}\right)} \tag{4.80}$$

(The salinity in the lock after Phase 4, $S_{L,S}$, can also be written as $S_{L,4}$.)

The phase-averaged discharges to and withdrawals from the fresh and salt side are then as follows:

◇ withdrawal from the salt side, with the prevailing salinity S_S:

$$V^-_{S,4} = V_{Ship,Down} + V_{U,S} \tag{4.81}$$

$$Q^-_{S,4} = \frac{V^-_{S,4}}{T_{open,S}} \tag{4.82}$$

◇ discharge to the salt side with salinity $S^+_{S,4}$:

$$V^{+}_{S,4} = V_{Ship,Up} + V_{U,S} + V_{flush} \tag{4.83}$$

$$Q^{+}_{S,4} = \frac{V^{+}_{S,4}}{T_{open,S}} \tag{4.84}$$

$$S^{+}_{S,4} = \frac{M_{S,4} - V^{-}_{S,4} \cdot S_S}{V^{+}_{S,4}} \tag{4.85}$$

◇ withdrawal from the fresh side, with the prevailing salinity S_F:

$$V^{-}_{F,4} = Q_{flush} T_{open,S} \tag{4.86}$$

$$Q^{-}_{F,4} = Q_{flush} \tag{4.87}$$

◇ there is no discharge to the lake side in this Phase

4.4 Cycle-averaged flows and salinities

Based on the volumes per locking cycle we now can, for each of the locking heads, determine the total transported volumes with their corresponding salinities. From these volumes the cycle-averaged flows can be determined.

4.4.1 Fresh side

The combined equation for the fresh side gives the total transport of the entire locking cycle. This equation is as follows:

$$M_F = M_{F,1} + M_{F,2} + M_{F,4} \tag{4.88}$$

Aside from that we have information about the amount of water that is withdrawn from the fresh side

$$V^{-}_{F} = V_{Level,LT} + V_{Ship,Up} + V_{U,F} + Q_{flush} \cdot 2 \cdot T_{open} \tag{4.89}$$

and the volume that is discharged to the fresh side

$$V^{+}_{F} = V_{Level,HT} + V_{U,F} + V_{Ship,Down} \tag{4.90}$$

By dividing both volumes by the time spent on a total locking cycle, we can determine the cycle-averaged flows. Each of these flows has a corresponding discharge, and can be connected to cells in a far-field model as a discharge or withdrawal:

◇ Withdrawal from the fresh side, with the prevailing salinity S_F:

$$Q^{-}_{F} = \frac{V^{-}_{F}}{T_{cycle}} \tag{4.91}$$

◇ Discharge to the fresh side with a to-be-determined average salinity:

$$Q_F^+ = \frac{V_F^+}{T_{cycle}}; S = S_F^+ \tag{4.92}$$

The average salinity for the water discharged to the fresh side is determined from the mass and volume transports:

$$S_F^+ = -\frac{\left(M_F - V_F^- S_F\right)}{V_F^+} \tag{4.93}$$

In case of stand-alone application, but also to compare with other locks or salt intrusion measure configurations, it can be useful to express the salt transport as a mass flux:

$$\dot{M}_F = \frac{M_F}{T_{cycle}} \tag{4.94}$$

4.4.2 Salt side

The combined equation for the salt side is:

$$M_S = M_{S,2} + M_{S,3} + M_{S,4} \tag{4.95}$$

Again, we can write down the volumes going to and from the salt side. For the withdrawal that is:

$$V_S^- = V_{Level,HT} + V_{Ship,Down} + V_{U,S,Flush} \tag{4.96}$$

and the volume that is discharged to the salt side

$$V_S^+ = V_{Level,LT} + V_{U,S,Flush} + V_{Ship,Up} + Q_{flush} \cdot 2 \cdot T_{open} \tag{4.97}$$

By dividing both volumes by the time spent on a total locking cycle, we can determine the cycle-averaged flows. Each of these flows has a corresponding discharge, and can be connected to cells in a far-field model as a discharge or withdrawal:

- ◇ Withdrawal from the salt side, with the prevailing salinity S_S:

$$Q_S^- = \frac{V_S^-}{T_{cycle}} \tag{4.98}$$

- ◇ Discharge to the salt side with a to-be-determined average salinity:

$$Q_S^+ = \frac{V_S^+}{T_{cycle}}; S = S_S^+ \tag{4.99}$$

The average salinity for the water discharged to the salt side is determined from the mass and volume transports:

$$S_S^+ = \frac{\left(M_S - V_S^- S_S\right)}{V_S^+} \tag{4.100}$$

In case of stand-alone application, but also to compare with other locks or salt intrusion measure configurations, it can be useful to express the salt transport as a mass flux:

$$\dot{M}_S = \frac{M_S}{T_{cycle}} \tag{4.101}$$

For an equilibrium state, with the lock operating with constant operation for long periods of time, it obviously holds that

$$\dot{M}_S = \dot{M}_F \tag{4.102}$$

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4.5 Numerical approach cycle-averaged values

The description in Chapter *Equations per locking phase* of how the transports and how the salinity in the lock chamber changes from phase to phase, also gives a recipe for calculating the cycle-averaged values of volumes and salinities. Namely, we can iteratively calculate our way through the locking cycle until the calculated value no longer change significantly. From these steady state values the cycle-averaged flows (discharges and withdrawals) can be determined, together with the salinities (see Section 4.5.1).

An alternative approach is setting up a system of equations (see Section 4.5.2). From Chapter *Equations per locking phase* and *Cycle-averaged flows and salinities* the essential equations can be selected, that together form a system of equations with unknowns. Solving this system of equations than resolves the unknowns that are necessary to calculate the cycle-averaged flows and salinities.

4.5.1 Iteratively calculating the locking cycle

In Chapter *Cycle-averaged flows and salinities* the expression for the flows (discharges and withdrawals) have been set up, but a few unknowns remain. These values arise in the locking cycle, as described in Chapter *Equations per locking phase*.

This cycle can then be considered iterative process: for fixed boundary conditions and after enough cycles, eventually these unknowns will converge to their respective values. To enter this iterative process, e.g. starting at LT 1 / HT 1, we only need an initial guess for the salinity of the lock chamber. Obviously this guess has to be higher than the salinity of the fresh side, and lower than that of the salt side. A good starting point would then be the average of the salinities of the boundary conditions.

In case of calculating through time for varying boundary conditions (e.g. a tide on the sea side, or a time-varying operation of the lock), the converged lock chamber salinity of the previous time step can be chosen as the initial guess. For slowly changing boundary conditions, the previous chamber salinity is a reasonable estimate. The closer the guess to the eventual solution, the fewer iterations are needed to converge.

The numerical approach for determining cycle-averaged values then consists of two steps:

1. Iteratively determining the unknown values
2. Calculate the discharges Q_F^+ with S_F^+ and Q_S^+ with S_S^+, and the withdrawals Q_F^- and Q_S^-.

4.5.2 System of equations

An alternative to the iterative approach as described above is setting up a system of equations in which the number of equations is equal to the number of unknowns. From the previous chapters the relevant equations can be selected, each with a number of unknowns. (The unknowns in this case are all values that cannot be directly calculated from the boundary conditions or input). Not all equations are linear, so it is necessary to repeatedly solve a linearized system of equations until convergence. In practice, this way of solving has very little advantage over calculating iteratively as described in *Iteratively calculating the locking cycle*. We therefore do not elaborate further on this approach.

4.5.3 Overview of output

By the formulation the steady state values of the following quantities are calculated, all as function of time:

M_F, $\dot{M}_F$, Q_F^-, Q_F^+, S_F^+, M_S, $\dot{M}_S$, Q_S^-, Q_S^+, S_S^+

Getting to these parameters is what the formulation was designed for: the mass transports (per cycle) and the fluxes and flows (cycle-averaged) that enter and exit the lock on both sides. Aside from that there are a few other parameters that can help interpret the output. These can be geometric parameters, like the volume of the lock chamber, or operational parameters like door-open times. It is also possible to export the cycle-averaged transports per locking phase.

Aside from that, a few other useful parameters can be determined. These parameters can help compare the D-SLE to more naive methods of determined the salt load, or with other theoretical or experimental relations.

4.5.3.1 Dimensionless salt transport

For the dimensionless salt transport over the lock per cycle, we use the parameter $Z_{fraction}$. This parameter is defined as a factor on the lock chamber volume times the difference in salinity between the boundary conditions:

$$M = Z_{fraction} V_L \cdot \Delta S \tag{4.103}$$

As such, $Z_{fraction}$ indicates what fraction of the lock chamber, in regular locking operation, exchanges and contributes to the salt transport.

In the process of calculating transports we get transports for both lock heads. Aside from that, the volume of the lock chamber, due to a difference in water level on both sides, is not always equal. Therefore, we have to use average values for these quantities. From this, $Z_{fraction}$ can be written as:

$$Z_{fraction} = \frac{\overline{M}}{\overline{V_L} \cdot (S_S - S_F)} = \frac{0.5 \cdot (M_F + M_S)}{0.5 \cdot (V_{L,F} + V_{L,S}) \cdot (S_S - S_F)} \tag{4.104}$$

4.5.3.2 Dimensionless door-open time

The dimensionless door-open time is T_{LE}/T_{open}. In the calculations the value of T_{LE} is determined per lock head, with the prevailing salinity difference. With that, the value of T_{LE} is not a direct function of the input, but is dependent on the calculations. To get to a T_{LE} that is only determined by input (boundary conditions and geometry), we define a variant: $T_{LE,FS}$. This quantity is based solely on the salinity difference over the lock. This parameter is not used in the calculations, but is sometimes used in determining auxiliary outputs, e.g. of the dimensionless door-open time T_{LE}/T_{open}:

$$c_{i,FS} = \frac{1}{2}\sqrt{g'\overline{H}} = \frac{1}{2}\sqrt{g\frac{\Delta\rho}{\overline{\rho}}\overline{H}} \approx \frac{1}{2}\sqrt{\frac{0.8\,(S_S - S_F)}{\overline{\rho}_{FS}}\left(\frac{H_F + H_S}{2}\right)} \tag{4.105}$$

$$T_{LE,FS} = \frac{2L}{c_{i,FS}} \tag{4.106}$$

4.6 Temperature and passive constituent transport

D-SLE primarily calculates the water and salt transport through a sea lock. Temperature is included as an input because it affects water density and therefore the salt-intrusion calculation. After that calculation, temperature is transported as a passive constituent. This transport principle is generalized to other passive constituents, such as tracers or sediment concentrations, that are transported with the water but do not influence the density or flow field.

The initial lock temperature is set with `initial_temperature_lock`; this value initializes both lake-side and sea-side temperature values for the lock.

Other passive constituents do not influence the density or flow field. They are identified by name through the host interface. In the D-SLE BMI implementation, a constituent is registered when its named BMI variable is first accessed. Initial values and boundary concentrations are supplied through that interface rather than by the core transport equations. User-configurable initial concentrations of arbitrary passive constituents in the lock are not currently supported; adding this as an explicit initialization feature is a possible future extension.

4.6.1 Cycle-average mode

In cycle-average mode, D-SLE uses the salinity result to derive the sea-water fraction of each output:

$$f = \frac{S_{\text{out}} - S_{\text{lake}}}{S_{\text{sea}} - S_{\text{lake}}}. \tag{4.107}$$

The same fraction is applied to every passive constituent:

$$c_{\text{out}} = c_{\text{lake}} + f\left(c_{\text{sea}} - c_{\text{lake}}\right). \tag{4.108}$$

When the sea and lake salinities are equal, D-SLE uses a zero fraction and returns the lake-side constituent value. The calculation is performed per active layer in a 3D coupling.

4.6.2 Phase-wise mode

In phase-wise mode, D-SLE maintains a constituent concentration in the lock and updates it from the water volumes exchanged during each phase. For levelling and gate-open phases, the update is a volume mass balance. For gate-open phases, the flushing passthrough volume is treated as water that enters and leaves at the lake-side concentration without mixing with the lock volume.

For a phase with lock volume before and after the phase, the updated lock concentration is:

$$\begin{aligned} c_{\text{lock,new}} = {} & \frac{c_{\text{lock}} V_{\text{before}} + c_{\text{lake}} V_{\text{from,lake}} + c_{\text{sea}} V_{\text{from,sea}}}{V_{\text{after}}} \\ & - \frac{c_{\text{lock}} V_{\text{to,lake}} + c_{\text{lock}}(V_{\text{to,sea}} - V_{\text{flush}}) + c_{\text{lake}} V_{\text{flush}}}{V_{\text{after}}}. \end{aligned} \tag{4.109}$$

The outflow concentration to the lake is the pre-phase lock concentration. The outflow concentration to the sea is the volume-weighted combination of the lock and passthrough contributions.

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During a flush-with-doors-closed phase, the lock volume is constant and the passive constituent follows a continuously stirred tank model:

$$c_{\mathrm{lock}}(t) = c_{\mathrm{lake}} + (c_{\mathrm{lock},0} - c_{\mathrm{lake}})e^{-\lambda t}, \qquad \lambda = \frac{Q}{V_{\mathrm{lock}}}. \tag{4.110}$$

Here, Q is the flushing discharge and V_{lock} is the lock volume. The volumetric decay rate is positive, so the constituent approaches the lake-side concentration from either direction.

This passive-constituent formulation differs from the salinity formulation during flushing because salinity accounts for salt mass and density-stratification effects. Consequently, a passive constituent configured to mirror salinity does not generally produce the same value as salinity during a flush-with-doors-closed phase.

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5 API

5.1 BMI API

The primary integration interface for the D-HYDRO and Delft3D FM repositories is the Basic Model Interface (BMI) implemented by the D-SLE library. DIMR loads the D-SLE shared library and calls this interface to initialize the model, exchange variables, advance time, and finalize the model. The same exported functions can be used by another BMI-compatible host.

The BMI entry points are exported by the `dsle` shared and static library targets. The DIMR coupling chapter documents the D-SLE variable-key namespace; this section documents the BMI lifecycle and function contract.

5.1.1 Lifecycle

A host normally calls the functions in this order:

1. Call `initialize` with the path to the D-SLE `.ini` file.
2. Exchange boundary conditions with `set_var` and retrieve model values with `get_var`.
3. Advance the model by calling `update` with a non-negative time interval in seconds.
4. Repeat the exchange and update steps until the simulation is complete.
5. Call `finalize` to release the loaded configuration and model state.

The BMI status convention is:

- `0`: success (`DIMR_BMI_OK`);
- `1`: failure (`DIMR_BMI_FAILURE`).

5.1.2 Variable access

The functions `set_var` and `get_var` use a string key to identify a value. Keys may contain a variable type, lock ID, and quantity separated by slashes:

```
<variable_type>/<lock_id>/<quantity>
```

The D-SLE coupling chapter lists the supported input and output quantities. Scalar quantities are exchanged through a pointer to one `double`. Layer-dependent quantities are exchanged as arrays of `double`; use `get_var_shape` to determine the number of active layers before allocating or reading an array.

5.1.3 Time and model information

The following exported functions provide model time information:

- `get_start_time`: return the configured start time as a timestamp;
- `get_end_time`: return the configured end time as a timestamp;
- `get_current_time`: return the current model time as a timestamp;
- `get_time_step`: return the model time step;
- `get_version_string`: return the D-SLE version string.

The exported `get_var_shape` function writes the dimensions of a requested variable to an integer array with six elements. For the current D-SLE variables, the first dimension contains the number of active layers and the remaining dimensions are zero.

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5.1.4 Direct C API and BMI API

The direct C API documented below exposes the salt-intrusion calculation itself through structures and functions in `dsle.h`. It is useful when an application wants to control parameter structures and phase stepping directly. The BMI API is the preferred interface when D-SLE is hosted by DIMR, D-Flow FM, or another BMI-compatible model framework.

5.2 Direct C API

5.2.1 Structures

5.2.1.1 Input

struct **dsle_param_t**

The parameter structure both for phase-wise calculation, and for steady state calculation.

double **lock_length**

The length of the lock in meters.

double **lock_width**

The width of the lock in meters.

double **lock_bottom**

The bottom of the lock in meters with respect to datum (e.g. mNAP).

double **num_cycles**

(Steady) The number of cycles (leveling from lake to sea and back again) the lock makes in a day.

double **door_time_to_open**

(Steady) The time it takes for the door to go from fully closed to fully (open in seconds.

double **leveling_time**

(Steady) The average time it takes to level the lock to the sea or lake level in seconds.

double **calibration_coefficient**

(Steady) The calibration coefficient on the time that the door is open.

double **symmetry_coefficient**

(Steady) The imbalance between the lake door and right door being open, should be in the range (0, 2). A value of 1.0 means that the lake and sea side door are open equally long.

double **ship_volume_sea_to_lake**

The water displacement of ships going from the sea to the lake in m^3.

double **ship_volume_lake_to_sea**

The water displacement of ships going from the sea to the lake in m^3.

double **salinity_lock**

The (initial) salinity of the lock in kg/m^3.

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double **head_sea**

The head of the sea in meters with respect to datum (e.g. mNAP).

double **salinity_sea**

The salinity of the sea in kg/m^3.

double **temperature_sea**

The temperature of the sea in degrees Celcius.

double **head_lake**

The head of the lake in meters with respect to datum (e.g. mNAP).

double **salinity_lake**

The salinity of the lake in kg/m^3.

double **temperature_lake**

The temperature of the lake in degrees Celcius.

double **flushing_discharge_high_tide**

The flushing discharge in $m3/s$ when the sea level is higher than (or equal to) lake level.

double **flushing_discharge_low_tide**

The flushing discharge in $m3/s$ when the lake level is strictly below the sea level.

double **density_current_factor_sea**

The factor by which to multiply the velocity of the density current on the sea side.

double **density_current_factor_lake**

The factor by which to multiply the velocity of the density current on the lake side.

double **distance_door_bubble_screen_sea**

Distance of the bubble screen on the lake side to the door in meters. Positive values mean that the screen is outside the lock. Negative values mean that the screen is inside the lock.

double **distance_door_bubble_screen_lake**

Distance of the bubble screen on the lake side to the door in meters. Positive values mean that the screen is outside the lock. Negative values mean that the screen is inside the lock.

double **sill_height_sea**

Sill height on the sea side in meters above the bottom of the lock.

double **sill_height_lake**

Sill height on the lake side in meters above the bottom of the lock.

double **rtol**

(Steady) The relative tolerance of the salinity in the lock after phase 4 to determine whether convergence has been reached.

double **atol**

(Steady) The absolute tolerance of the salinity in the lock after phase 4 to determine whether convergence has been reached.

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5.2.1.2 Steady state output

These structures are output by *dsle_calc_steady()*. Note that *dsle_aux_results_t* is an optional output of this function, and is not output/calculated by default.

struct **dsle_results_t**

For mass and salt transport the definition is such that positive values are in the direction lake $\rightarrow$ lock $\rightarrow$ sea. Negative values mean that there is a net withdrawal of salt from the sea or net salt load on the lake.

double **mass_transport_lake**

The mass transport of salt over the lake head in kg.

double **salt_load_lake**

The average salt transport to the lake kg/s.

double **discharge_from_lake**

The average discharge from the lake to the lock in $m3/s$.

double **discharge_to_lake**

The average discharge from the lock to the lake in $m3/s$.

double **salinity_to_lake**

The average salinity of the water going from the lock to the lake in kg/m^3.

double **mass_transport_sea**

The mass transport of salt over the sea head in kg/m^3.

double **salt_load_sea**

The average salt transport to the sea kg/s.

double **discharge_from_sea**

The average discharge from the sea to the lock in $m3/s$.

double **discharge_to_sea**

The average discharge from the lock to the sea in $m3/s$.

double **salinity_to_sea**

The average salinity of the water going from the lock to the sea in kg/m^3.

struct **dsle_aux_results_t**

Additional results that can be calculated for steady state operation.

double **z_fraction**

The dimensionless salt transport per cycle. It is defined as a factor on the lock volume times the difference in salinity between the lake and sea side.

$$M = Z_{fraction} V_{lock} \cdot \Delta S$$

This way it represents what part of the lock, in the regular locking process, is exchanged by the density current and contributes to the salt transport.

Because the salt transports are per head, and the volume of the lock is not always equal on sea and lake side, average values are used for these.

$$Z_{fraction} = \frac{\overline{M}}{\overline{V}_{lock} \cdot (S_{sea} - S_{lake})} = \frac{0.5 \cdot (M_{lake} + M_{sea})}{0.5 \cdot (V_{lock,lake} + V_{lock,sea}) \cdot (S_{sea} - S_{lake})}$$

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double **dimensionless_door_open_time**

The dimensionless door open time is T_{LE}/T_{open}. In this calculation the value for T_{LE} is calculated per lock head, with the corresponding salinity difference. That means that T_{LE} is not just a function of the input, but is dependent on the calculation routines, and there are two values (one for each lock head). To get to a single T_{LE} that is determined by the geometry and boundary conditions, we define a variant of $T_{LE,lake-sea}$ based on the density difference over the lock.

$$c_{i,lake-sea} = \frac{1}{2}\sqrt{g'\overline{H}} = \frac{1}{2}\sqrt{g\frac{\Delta\rho}{\bar{\rho}}\overline{H}} \approx \frac{1}{2}\sqrt{g\frac{0.8\left(S_{sea}-S_{lake}\right)}{\bar{\rho}_{lake-sea}}\left(\frac{H_{lake}+H_{sea}}{2}\right)}$$

$$T_{LE,lake-sea} = \frac{2L}{c_{i,lake-sea}}$$

double **volume_to_lake**

The volume that is discharged to the lake per locking cycle in m^3.

double **volume_from_lake**

The volume that is withdrawn from the lake per locking cycle in m^3.

double **volume_to_sea**

The volume that is discharged to the sea per locking cycle in m^3.

double **volume_from_sea**

The volume that is withdrawn from the sea per locking cycle in m^3.

double **volume_lock_at_lake**

The volume of the lock when it is at sea level in m^3.

double **volume_lock_at_sea**

The volume of the lock when it is at sea level in m^3.

double **t_cycle**

The time it takes to complete one locking cycle in seconds.

double **t_open**

The average value of the door open time on the lake and sea side, i.e. the average of *dsle_aux_results_t.t_open_lake* and *dsle_aux_results_t.t_open_sea*.

double **t_open_lake**

The time the door is open on the lake side per locking cycle in seconds.

double **t_open_sea**

The time the door is open on the sea side per locking cycle in seconds.

double **salinity_lock_1**

The salinity of the lock after phase 1 in kg/m^3.

double **salinity_lock_2**

The salinity of the lock after phase 2 in kg/m^3.

double **salinity_lock_3**

The salinity of the lock after phase 3 in kg/m^3.

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double **salinity_lock_4**

The salinity of the lock after phase 4 in kg/m^3.

dsle_phase_transports_t **transports_phase_1**

The phase transports in phase 1. See *dsle_phase_transports_t*

dsle_phase_transports_t **transports_phase_2**

The phase transports in phase 2. See *dsle_phase_transports_t*

dsle_phase_transports_t **transports_phase_3**

The phase transports in phase 3. See *dsle_phase_transports_t*

dsle_phase_transports_t **transports_phase_4**

The phase transports in phase 4. See *dsle_phase_transports_t*

5.2.1.3 Phase-wise output

struct **dsle_phase_state_t**

The state of the lock. Note that some of these values are redundant, but it is faster to store them than recalculate them every time.

double **salinity_lock**

The salinity of the water in the lock in kg/m^3.

double **saltmass_lock**

The amount of salt in the lock in kg.

double **head_lock**

The head of the lock in meters with respect to datum (e.g. mNAP).

double **volume_ship_in_lock**

The water displacement of a ship inside the lock in m^3.

struct **dsle_phase_transports_t**

For mass and salt transport the definition is such that positive values are in the direction lake $\rightarrow$ lock $\rightarrow$ sea. Negative values mean that there is a net withdrawal of salt from the sea or net salt load on the lake.

double **mass_transport_lake**

The mass transport of salt over the lake head in kg.

double **volume_from_lake**

The volume of water that goes from the lake to the lock in m^3.

double **volume_to_lake**

The volume of water that goes from the the lock to the lake in m^3.

double **discharge_from_lake**

The average discharge of water going from the lake to the lock in $m3/s$.

double **discharge_to_lake**

The average discharge of water going from the lock to the lake in $m3/s$.

double **salinity_to_lake**

The average salinity of the water going from the lock to the lake in kg/m^3.

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double **mass_transport_sea**

The mass transport of salt over the sea head in kg.

double **volume_from_sea**

The volume of water that goes from the sea to the lock in m^3.

double **volume_to_sea**

The volume of water that goes from the the lock to the sea in m^3.

double **discharge_from_sea**

The average discharge of water going from the sea to the lock in $m3/s$.

double **discharge_to_sea**

The average discharge of water going from the lock to the sea in $m3/s$.

double **salinity_to_sea**

The average salinity of the water going from the lock to the sea in kg/m^3.

5.2.2 Functions

int **dsle_initialize_state**(const *dsle_param_t* *p, *dsle_phase_state_t* *state, double salinity_lock, double head_lock)

Fill the state with an initial condition for an empty (no ships) lock.

int **dsle_step_phase_1**(const *dsle_param_t* *p, double t_level, *dsle_phase_state_t* *state, *dsle_phase_transports_t* *results)

Perform step 1: leveling to lake side

int **dsle_step_phase_2**(const *dsle_param_t* *p, double t_open_lake, *dsle_phase_state_t* *state, *dsle_phase_transports_t* *results)

Perform step 2: door open to lake side:

- ◇ Ships leaving the lock chamber
- ◇ Lock exchange with or without flushing
- ◇ Ships entering the lock chamber

int **dsle_step_phase_3**(const *dsle_param_t* *p, double t_level, *dsle_phase_state_t* *state, *dsle_phase_transports_t* *results)

Perform step 3: leveling to sea side

int **dsle_step_phase_4**(const *dsle_param_t* *p, double t_open_sea, *dsle_phase_state_t* *state, *dsle_phase_transports_t* *results)

Perform step 4: door open to sea side:

- ◇ Ships leaving the lock chamber
- ◇ Lock exchange with or without flushing
- ◇ Ships entering the lock chamber

int **dsle_step_flush_doors_closed**(const *dsle_param_t* *p, double t_flushing, *dsle_phase_state_t* *state, *dsle_phase_transports_t* *results)

Flush the lock with the doors closed.

void **dsle_param_default**(*dsle_param_t* *p)

Fill a `dsle_param_t` with default values.

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int **dsle_calc_steady**(const *dsle_param_t* *p, *dsle_results_t* *results,
dsle_aux_results_t *aux_results)

Calculate the salt intrusion for a set of parameters, assuming steady operation.

const char ***dsle_error_msg**(int code)

Get error message corresponding to error code.

const char ***dsle_version**()

Get version string.

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6 Coupling of D-Flow FM with with D-SLE

6.1 Introduction

The Wanda-Locks software suite of Deltares is available for the simulation of salt intrusion in sea locks, and it can be coupled to Delft3D-FLOW via the COSUMO toolbox. However, this results into very computationally intensive simulations. Therefore, another approach has been developed that is much less computationally demanding, called D-SLE. D-Flow FM can be coupled to the "Sea Lock Exchange" software program of Deltares, which is called the "Zeesluisformulering" in Dutch. The D-SLE software is available in Python and as a C-library and has been applied to many sea locks. The technical documentation of D-SLE can be found at https://libzsf.readthedocs.io/en/latest/theory/index.html.

Based on the water level and the salinity concentration at lateral locations, discharges 'from sea to lake' and 'from lake to sea' are computed by the D-SLE. In D-Flow FM these discharges are modelled via laterals. The sea lock itself is represented in the D-Flow FM model area as a closed or dry area, as illustrated in Figure 1.

6.2 Coupling of D-Flow FM with D-SLE

A coupled D-Flow FM-D-SLE model can be run as an Integrated Model from within the D-Flow FM User Interface, or from a command prompt using the DIMR program (Deltares Integrated Model Runner).

In case of a coupled D-Flow FM-D-SLE model

- the D-Flow FM model and the D-SLE model exchange water discharge and salinity through *laterals*.
- the D-Flow FM model provides boundary conditions to the D-SLE model, i.e. water level and salinity at the lake and sea sides. The D-SLE model will in turn provide lateral input to the D-Flow FM model, i.e. the discharge extracted from and the discharge and salinity deposited to the lake and sea.
- laterals in D-Flow FM may consist of multiple grid cells. All exchanged data is aggregated into a single value per lateral before the exchange with D-SLE.
- in case of 3D models the exchange of water and salinity can be subdivided over multiple layers.
- it is advised to specify different lateral locations for inflow and outflow at both sides of the sea lock, to prevent unphysical mixing in the D-Flow FM model. This results into four laterals per sea lock.

In addition to salinity, D-SLE supports the transport of *passive constituents* and temperature through the sea lock. Passive constituents (e.g. tracers, sediment concentrations) are transported by the same water volumes computed by the salt intrusion model but do not influence the densityor flow field. Because of this, their transport behavior can be calculated using a simple volume mass balance approach, without the need to solve additional transport equations. While temperature is an input for the salt intrusion model and does influence density, it afterwards also behaves as a passive constituent.

Figure 1 shows a simple D-Flow FM model in which a sea lock is located in the middle of a D-Flow FM model domain. The cells with red triangles represent the sea lock via dry points in D-Flow FM and are therefore non-computational cells; note that it is also possible to represent dry points by simply removing the grid cells. In this example the lake is on the left and the sea on the right side of the model. There are four lateral locations, denoted by four blue polygons. For both the lake side and the sea side the lateral locations for inflow and outflow are separated. In this example, all four laterals consists of two grid cells.

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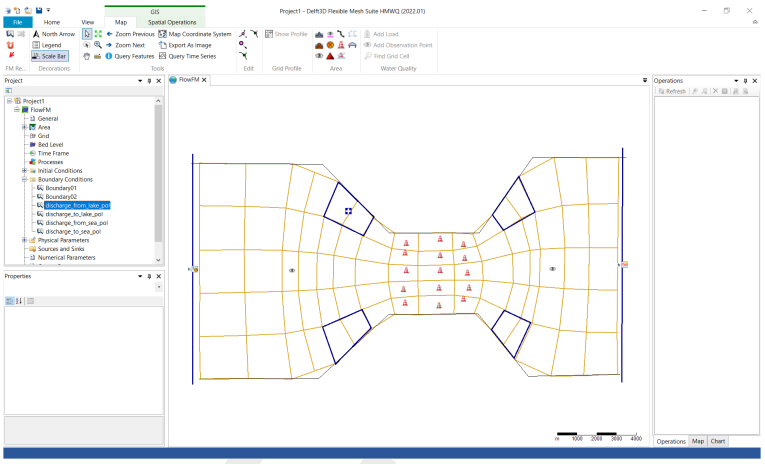

Fig. 1: *An example of a simple D-Flow FM model in the Graphic User Interface (GUI). The sea lock is in the middle, the lake on the left side and the sea on the right side.*

6.3 Processing of the received lateral data items in D-Flow FM

In this section, we describe the processing of the lateral data items in D-Flow FM. D-SLE expects and returns a single value per lateral and per layer. In D-Flow FM, in the horizontal direction, the single value from D-SLE will be distributed over all cells in the lateral after exchange with D-SLE. In turn, the values of all the cells will be aggregated before exchanging them to D-SLE.

Water volume

At each lateral location, the water volume is the water volume per horizontal layer, which is computed as the sum of the volumes of the individual cells on this layer.

Distribution of the D-SLE discharge output to different layers

The water volume per horizontal layer is used to determine active layers, i.e. layers with non-zero water volume. To distribute discharge output of D-SLE, the vertical relative location of the `flow_profile` is first projected to the active layers. Vertical locations with positive profile are layers to which the output of D-SLE is pumped into the D-Flow FM model. Vertical locations with negative profile gives layers from where water is extracted from D-Flow FM model. For each layer, a the relative profile determines the discharge exchanged.

Distribution of the lateral discharge to different cells per layer

Lateral discharge (per layer) is communicated between D-SLE model and D-Flow FM model via BMI. For each lateral location, after the D-Flow FM model receives the discharge value per layer (from D-SLE model), D-Flow FM distributes the discharge over all the cells in the lateral volume defined by a polygon and a layer. The distribution is proportional to the available volume in a cell.

The algorithm for distribution of the lateral discharge in a 3D model is as follows. Let $i_layer = 1, ..., kmx$ be the layer indices where kmx is the total number of layers in 3D models of D-Flow FM. Moreover, let $ncell$ be the total number of cells at one lateral location. The following variables are needed for distributing the lateral discharge:

- ◇ Volume for each cell at each layer, denoted by V_{i_layer,i_cell}.

◇ Total volume at layer i_layer, denoted by V_{i_layer}. Therefore,

$$\sum_{i_cell=1}^{ncell} V_{i_layer,i_cell} = V_{i_layer}.$$

◇ Discharge for each cell at each layer, denoted by Q_{i_layer,i_cell}.
◇ Total discharge at layer i_layer, denoted by Q_{i_layer}. Therefore,

$$\sum_{i_cell=1}^{ncell} Q_{i_layer,i_cell} = Q_{i_layer}.$$

The following relation holds:

$$\frac{Q_{i_layer,i_cell}}{Q_{i_layer}} = \frac{V_{i_layer,i_cell}}{V_{i_layer}}. \tag{6.1}$$

Therefore, Q_{i_layer,i_cell} can be computed by:

$$Q_{i_layer,i_cell} = \frac{V_{i_layer,i_cell}}{V_{i_layer}} \cdot Q_{i_layer}. \tag{6.2}$$

Eq. (6.2) has been implemented.

Concentration

The exchanged concentration of, e.g., salinity in D-Flow FM is computed per layer in 3D models. In case of a 2D model, it can be regarded as having only one layer.

DIMR runs the D-Flow FM and D-SLE models in a number of update steps. At each update step, the models run over an exchange interval, whose interval is configured in a DIMR configuration file. It can happen that over an exchange interval, a D-Flow FM model runs over a number of time steps. For each update process, D-Flow FM computes the input concentration for D-SLE as the average concentration over all grid cells in the lateral and over the exchange time interval. The formula implemented in D-Flow FM for computing the average concentration at one layer, denoted by c_{i_layer}, reads:

$$c_{i_layer} = \frac{\sum_{j}\sum_{k}^{ncell} dt_j \cdot V_k \cdot c_k}{T\sum_{k}^{ncell} V_k}, \tag{6.3}$$

where dt_j is the j^{th} computational time step during the update process, k is one cell on layer i_layer, T is the exchange time interval, and V_k and c_k are the volume and concentration of cell k, respectively. The exchange time interval denotes the interval of communication between D-Flow FM and D-SLE. Eq. (6.3) shows that values are accumulated over an exchange time interval T before a concentration value is communicated towards the D-SLE module.

Salinity input to D-SLE

For 3D model, the `flow_profile` is not used to determine salinity input to D-SLE from D-Flow FM. Based on experience, it is decided to use depth-average salinity instead.

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7 Support

The D-SLE source, tests, and build integration are maintained in the Delft3D repository. Report defects and questions through the repository's issue tracker or the standard Deltares support channel.

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References

Deltares, 2026. *D-Flow FM Hydro- and Morphodynamics User Manual; Released for Delft3D FM Suite 2D3D*. Deltares, Delft.

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