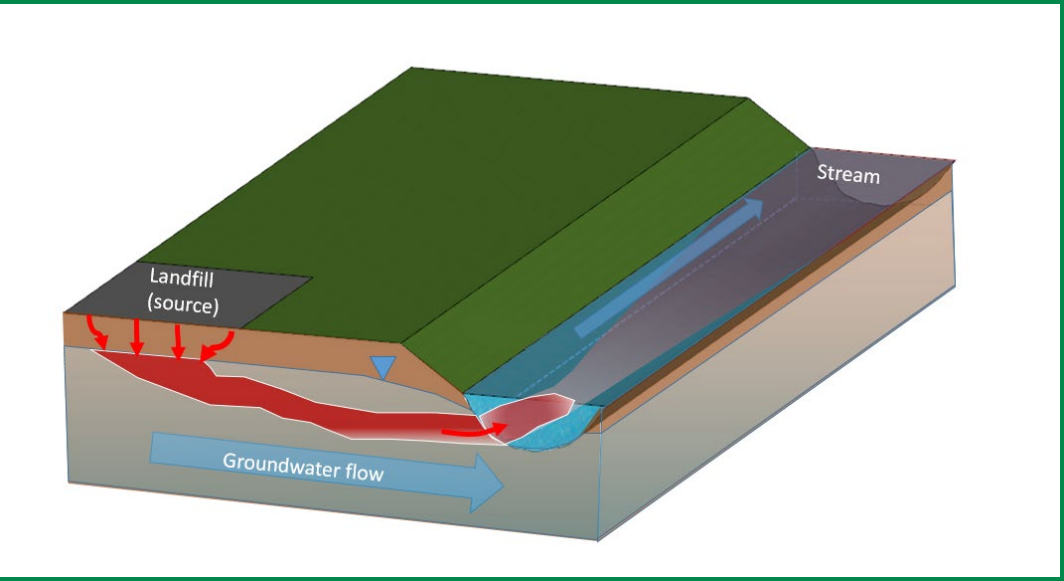
Ministry of Environment of Denmark
Environmental Protection Agency

Methodology for risk assessment of stream water contamination by landfills

Mixing of landfill leachate plumes in streams



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Forbehold

Denne rapport er en del af ”Metodik til stedsspecifik risikovurdering ved deponering af affald”. Rapporten er foreløbig og af oplysende karakter, og indholdet kan på nuværende tidspunkt ikke alene danne grundlag for en konkret sagsbehandling og myndighedsafgørelse. Baggrunden for dette er, at Miljøstyrelsen arbejder for at afklare særlige forhold omkring vandrammedirektivets betydning for stedsspecifik vurdering af deponeringsanlæg og påvirkningen heraf i receptor. Afklaringerne kan give anledning til konsekvensrettelser i metodikken, som den er formuleret for nuværende, og det kan være nødvendigt at rettelserne skal indarbejdes i metodikkens værktøjer herunder modelværktøjer, brugervejledninger og dokumentationsrapporter. Således må offentliggjorte rapporter og værktøjer under metodikken for nuværende betragtes som foreløbige.

Miljøstyrelsen offentliggør rapporter og indlæg vedrørende forsknings- og udviklingsprojekter inden for miljøsektoren. Det skal bemærkes, at en sådan offentliggørelse ikke nødvendigvis betyder, at det pågældende indlæg giver udtryk for Miljøstyrelsens synspunkter. Offentliggørelsen betyder imidlertid, at indlægget udgør et væsentligt indlæg i debatten omkring den danske miljøpolitik.

Risikovurderingsværktøjet er beregningsteknisk forberedt til at kunne regne med nedbrydning når et bedre datagrundlag er tilvejebragt. Derfor indgår nedbrydning i sammenfatningen, brugervejledninger og som en del af transportmodellen. Miljøstyrelsen finder på nuværende tidspunkt ikke tilfredsstillende dokumentation for at nedbrydning kan indgå som en aktiv del i sagsbehandlingen ved brug af værktøjet. Såfremt at der på et senere tidspunkt tilvejebringes ny viden er Miljøstyrelsen åben for at lade nedbrydning indgå. Det betyder at metoden er forberedt til at inkludere nedbrydning, men at Miljøstyrelsen mangler den nødvendige viden for at kunne vurdere denne i sagsbehandlingen. Ny viden kan bl.a. bestå i en opdateret samlet videnskabelig rapport, hvor det er beskrevet, hvorledes der kan regnes med nedbrydning konkret i perkolatfaner fra deponeringsanlæg.

Content

Forord

Miljøstyrelsen, Dansk Affaldsforening og DepoNet har i samarbejde udviklet en "*Metodik til stedsspecifik risikovurdering ved deponering af affald*". Arbejdet er gennemført med opbakning fra branchen, og der har været afholdt møder, hvor branchen har bidraget med kommentarer og input til metodikken.

Metodik til stedsspecifik risikovurdering ved deponering af affald består af flere moduler og værktøjer, som er opsummeret i nedenstående oversigt.

- **Anvendelse af metodik til risikovurdering ved deponering af affald**
- **Eksempler på anvendelse af metodik**

- **Modul 1: Beskrivelse af kilden og kildestyrken**
  - Excelbaseret model til estimering af kildestyrken som funktion af tiden
  - Brugervejledning til kildestyrkemodellen
  - Dokumentationsrapport for Fase 1: Konceptuelle modeller
  - Dokumentationsrapport for Fase 2: Opbygning af kildestyrkemodel
- **Modul 2: Stoftransport i jord og grundvand**
  - Modelværktøj - GrundRisk Landfill: Analytisk model til estimering af stoftransport i umættet og mættet zone (brugerflade baseret på Matlab)
  - Brugervejledning til GrundRisk Landfill
  - Dokumentationsrapport for udvikling og tilpasning af GrundRisk modellen til brug for deponeringsanlæg og lossepladser (GrundRisk Landfill)
  - Retningslinjer for opstilling af numerisk model til stoftransport i jord og grundvand
- **Modul 3: Udsivning, opblanding og vurdering i overfladevand**
  - Notat om opblanding af perkolatforurenet grundvand i overfladevande samt vurdering af påvirkning i såvel grundvand som overfladevand
  - Dokumentationsrapport for udvikling af model for opblanding af perkolatforurenet grundvand i vandløb
  - Modelværktøj - Mixing of landfill leachate plumes in streams (brugerflade baseret på Matlab)
  - Brugervejledning til modellen - Mixing of landfill leachate plumes in streams

Der er i projektet endvidere gennemført en vurdering af miljømæssige og økonomiske konsekvenser ved stedsspecifik risikovurdering ved deponering af affald.

Modelværktøjer samt dokumentationsrapporter er samlet på Miljøstyrelsens hjemmeside og kan tilgås via Dansk Affaldsforenings og DepoNets hjemmesider.

Denne rapport er udarbejdet som en delopgave under **Modul 3: Udsivning, opblanding og vurdering i overfladevand.**

Følgende organisationer og personer har deltaget i arbejdet:

Styregruppe:
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COWI ved Lizzi Andersen og Steen Stentsøe, Danish Waste Solutions ved Ole Hjelmar, Erik Aagaard Hansen og René Møller Rosendal, ECN ved André van Zommern

Modul 2: Stoftransport i jord og grundvand
DTU Miljø ved Luca Locatelli, Poul L. Bjerg og Philip J Binning
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Modul 3: Udsivning, opblanding og vurdering af påvirkning i overfladevand og grundvand
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Rambøll ved Dorte Harrekilde

Vurdering af konsekvenser i relation til at overgå til stedsspecifik risikovurdering ved deponering af affald
COWI ved Steen Stentsøe, Lars Grue Jensen og Tage Vikjær Bote

Anvendelse af metodik til risikovurdering ved deponering af affald
COWI ved Tage Bote Kjær, Danish Waste Solutions ved Ole Hjelmar, DAKOFA ved Jette Bjerre Hansen.

Introduktion til metodik for risikovurdering ved deponering af affald

Baggrund

I Danmark har vi gennem mange år haft fokus på at beskytte miljøet omkring de danske deponeringsanlæg. EU's deponeringsdirektiv, som indeholder en række foranstaltninger i forhold til miljøbeskyttelse, blev i det væsentligste implementeret i 2001 i Danmark, og senest implementerede vi i 2009 EU's rådsbeslutninger om kriterier og procedurer for modtagelse af affald til deponering. Ved den danske implementering blev Deponeringsdirektivets krav til miljøbeskyttelse tilpasset de danske forhold ud fra nogle generelle betragtninger, herunder principperne om kystnærhed / ikke-kystnærhed, anlægsfaktorer samt anlægsklasser. Især kystnærhedsprincippet har vist sig at give visse udfordringer, og senest i 2020 må der efter de nuværende regler ikke længere modtages blandet affald til deponering på ikke-kystnære enheder. Branchen har derfor ønsket at få mulighed for at kunne gennemføre en konkret og stedsspecifik vurdering af miljøpåvirkningen fra det enkelte deponeringsanlæg, som et kvalificeret alternativ til de generelle krav i lovgivningen. Samtidig har branchen længe manglet et egentligt værktøj til at kunne estimere miljøpåvirkningen fra deponering af affald som funktion af tiden, og som vil kunne danne grundlag for et kvalificeret estimat af længden af efterbehandlingstiden. Dette er nødvendigt for beregning af den krævede sikkerhedsstillelse.

En metodik til vurdering af påvirkning af jord og vandmiljø fra deponeringsanlæg vil derfor kunne bidrage til at få kvalificeret svar på de mange spørgsmål, som er helt centrale i forbindelse med etablering, drift og afslutning af deponeringsanlæg.

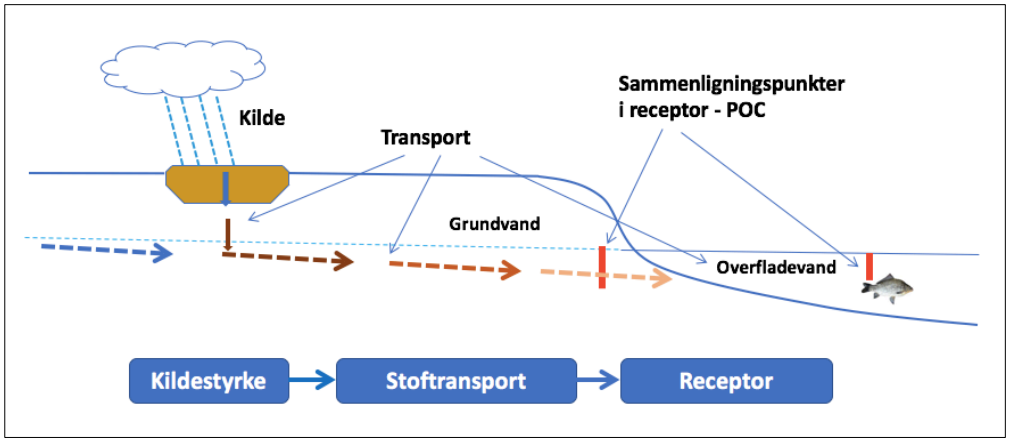
Metodik til risikovurdering ved deponering af affald

Dansk Affaldsforening, Miljøstyrelsen og DepoNet er derfor gået sammen om at udvikle en metodik til stedsspecifik risikovurdering ved deponering af affald i forhold til at synliggøre forureningspåvirkningen af det omkringliggende miljø; grundvand, overfladevand samt natur.

Metodikken finder anvendelse for:

- Alle deponeringsanlæg i drift (kystnære og ikke kystnære)
- Afsluttede deponeringsanlæg i efterbehandling
- Udvidelser af bestående deponeringsanlæg
- Planlægning af eventuelle nye deponeringsanlæg
- Nedlukkede lossepladser
- Nedlagte ukontrollerede lossepladser under den offentlige indsats administreret af regionerne

De forskellige anlægstyper er nærmere beskrevet i Miljøstyrelsen (2018b). Metodikken er baseret på nyeste viden samt de grundlæggende principper, som også er anvendt i forbindelse med fastsættelse af acceptkriterier for modtagelse af affald på deponeringsanlæg (Bekendtgørelse om deponeringsanlæg, BEK 719:2011). Principperne er illustreret i nedenstående figur.



Afhængig af de stedsspecifikke forhold omfatter metodikken flere af følgende elementer; stoffrigivelse fra det deponerede affald i kilden som funktion af tiden, stoftransport gennem en umættet og mættet zone samt stofudsivning til overfladevand, opblanding og vurdering af påvirkningen i receptor.

Metodikken er opbygget i moduler, og hvor det har været muligt anvendes en iterativ arbejdsproces, hvor metodikken indledningsvis er simpel, generisk og konservativ. Efter behov er det muligt at anvende stedsspecifikke data i modellen og inkludere mere avancerede vurderinger.

Følgende er indeholdt i metodikken:

Anvendelse af metodik til risikovurdering ved deponering af affald
Sammenfatningen giver en overordnet beskrivelse af tilgangen anvendt i metodikken samt en trinvis beskrivelse af metodikkens anvendelse. Der gives på hvert trin henvisninger til de konkrete værktøjer, der foreslås anvendt. Sammenfatningen indeholder også et overblik over de forhold, som det ikke har været muligt at afklare endeligt i metodikken samt anbefalinger til hvordan metodikken kan forbedres.

Modul 1: Beskrivelse af kilden og kildestyrken
Der er opbygget en excel-baseret model til estimering af kildestyrken. Modellen kræver stedsspecifikke data for kildens fysiske udformning samt data for stoffrigivelse (perkolatkoncentration) og perkolatdannelse over tid. Såfremt stedsspecifikke data for stoffrigivelse og perkolatdannelse ikke er tilgængelige, er der i modellen indarbejdet en mulighed for at anvende default værdier. Modellens output beskriver stofkoncentration og perkolatmængde fra kilden som funktion af tiden i overgangen mellem kildens bund og det omkringliggende miljø (kildestyrken). Der er udarbejdet en brugervejledning til modellen samt 2 baggrundsrapporter om principper for opstilling af model samt valg og forudsætninger.

Modul 2: Stoftransport i jord og grundvand

Modul 3: Udsivning, opblanding og vurdering i overfladevand
Der er udarbejdet et notat, som giver et overblik over, hvilke receptorer der er relevante at inddrage i forbindelse med vurdering af miljøpåvirkningen fra deponeringsanlæg samt i hvilke situationer. Notatet sammenfatter kriterier for fastsættelse af sammenligningspunktet (point of compliance), miljøkrav og –mål samt praksis for udpegning af blandingszoner. Der gives endvidere et overblik over gældende lovgivning for receptorer.

Udsivning af perkolatforurenet grundvand til vandløb har været et særligt opmærksomhedspunkt. Der er opstillet en model til belysning af, hvordan stofudsivning og -spredning i vandløbet sker fra en bred front i brinken, og der er givet anbefalinger til, hvordan påvirkningen af vandløbet vurderes. Der er udarbejdet en brugervejledning til modellen samt en dokumentationsrapport for udviklingen.

Vurdering af miljømæssige og økonomiske konsekvenser
Der er gennemført en vurdering af de miljømæssige og økonomiske konsekvenser for et deponeringsanlæg ved anvendelse af en stedsspecifik tilgang til vurdering af risiko for påvirkning af det omkringliggende miljø fra påvirkninger relateret til frigivelse af perkolat. Vurderingen omfatter konsekvenserne for det enkelte anlæg og på grundlag heraf er de overordnede konsekvenser ved metodikkens anvendelse for deponering af affald i Danmark vurderet.

Contents

Abbreviations

C_{max}	Maximum concentration in streams
C_{mix}	Fully mixed concentration in streams
C_{mz}	Maximum concentration at the downstream edge of the calculated mixing zone
CMD	Contaminant Mass Discharge
EQS	Environmental Quality Standard
L_{mix}	Mixing distance
POC	Point of Compliance

1. Introduction

1.1 Aim of the project

The current report focuses on the processes in play when a leachate plume originating from a landfill reaches and dilutes in streams. An analytical model for the evaluation of the contaminant mixing and dilution in streams is presented and a general methodology is proposed for appointing point of compliance (POC) in the stream for comparison with relevant environmental quality standards (EQS). The results of this report are used as an input for discussion with the relevant authorities on the impact of landfills on streams, and how to evaluate them in a systematic manner.

This model is directly used in connection with other models in the framework of a risk assessment tool for the contamination of groundwater and surface water by landfills (Miljøstyrelsen 2018a, b).

As examples of the applicability of the model the expected dilution is estimated for selected contaminants in streams from the leaching of three landfills selected for this project: Tandskov, Faaborg and Hørløkke in Denmark.

2. Dispersion and dilution of leachate contaminant in streams

2.1 Overview of the contaminant transport from landfill to streams

When examining the possible contamination from a landfill to surface water, several distinctive steps can be considered. These steps are illustrated in Figure 1. The first step is the leaching of contaminants from the landfill into the ground. (2) The contaminants reach the groundwater and will be transported with it. (3) If the hydrological conditions are favorable, this groundwater flow will interact with the stream water and the contaminant may enter the stream, and will finally be dispersed and diluted (4).

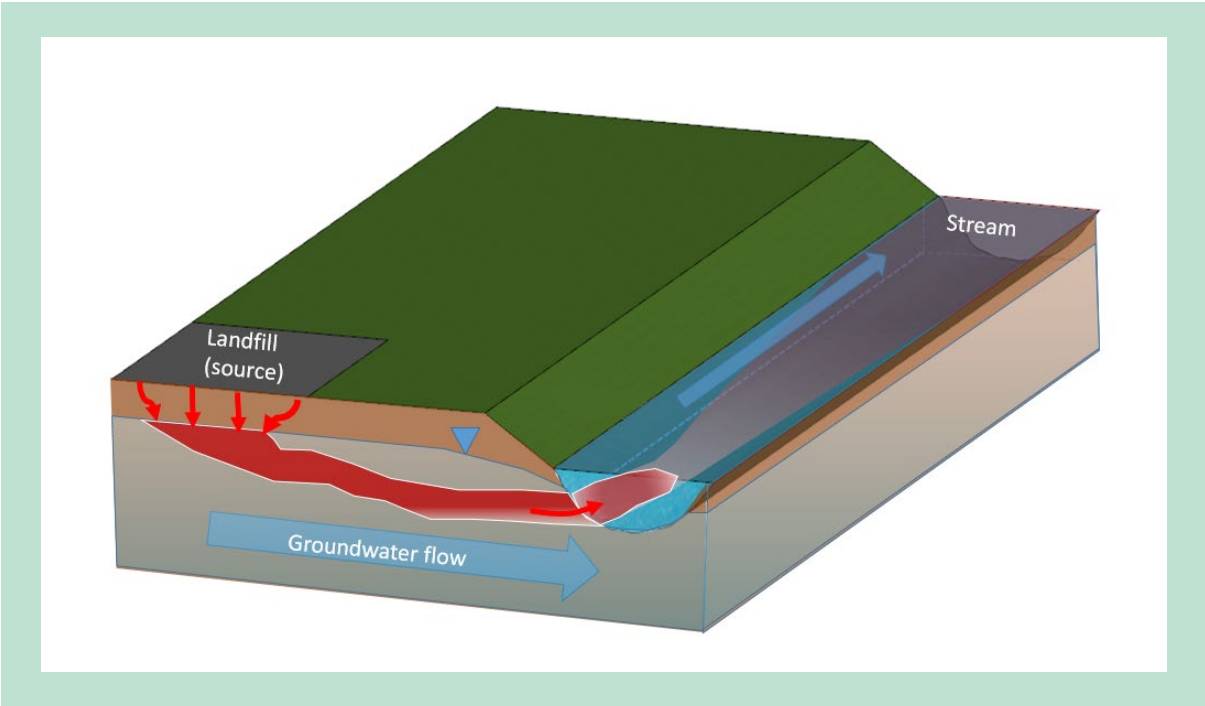


FIGURE 1. Schematic representation of the transport of contaminant from a landfill to a stream showing leaching to the groundwater, transport by groundwater and discharge into a stream prior to spreading and mixing

This report focuses on the last part of the transport, i.e. the dispersion and the dilution of the contaminant when entering the streams. Leaching of contaminant from landfills and transport in aquifer are addressed in other reports and will not be discussed further here (see Miljøstyrelsen 2018a, b for details).

2.2 Dispersion and mixing processes of contaminant into streams

When the contaminant seeps into the stream from groundwater, it will be transported with the stream flow, be diluted and mixed into it. In the vicinity of the point of discharge (the seeping zone) into the stream, the initial momentum of the contaminant discharge and buoyancy effect

determinates the dilution. Further downstream, the contaminant starts spreading transversally into the stream mostly by turbulence induced by shear velocity effect while being transported downstream simultaneously as illustrated in Figure 2. At a given point, the contaminant will be entirely mixed across the stream.

FIGURE 2. Illustration of contaminant mixing in the Rhine River by dye tracer experiment. Tracer is released from the left outside the picture (bright color), stream flows towards right. (Unknown source)

3. The assessment of contaminant concentration in streams posed by contaminated sites

The quantities and relevant definitions for comparison of contaminant concentration in stream water to the associated Environmental Quality Standard (EQS) are here reviewed and illustrated in Figure 3.

3.1 Mixing zone and calculated mixing zone

Mixing zones are used for controlled discharges to surface waters from companies such as regulation of waste water streams from production facilities, but also for controlled landfills regulated under the Environmental Protection Act. In general, a mixing zone is defined as a zone adjacent to the point of contaminant discharge where compound concentrations can exceed the relevant EQS “if they do not affect the compliance of the rest of the body of surface water with those standards”. These concentrations are opposed to so-called ambient concentrations beyond this mixing zone (Article 4, European Union, 2008).

The extent of the mixing zone is not legally defined by the European law, but the approach should be clearly described. However, a length of 10 times the stream width is suggested coupled to a fixed maximum to “ensure that the extent of the mixing zone is restricted to the proximity of the discharge point” (European Union, 2010). The maximum mixing zone dimensions of up to 10 times the stream width are adopted by the Danish Environmental Protection Agency (Miljøstyrelsen, n.d.).

In the context of contaminated sites under the Danish Soil Act ("Jordforureningsloven"), an initial screening is carried out by the Danish Regions to investigate the potential influence of contaminated sites on nearby surface waters. In this specific context, zones with a function similar to mixing zones are defined for the contaminated sites. These zones are defined as calculated mixing zones ("beregningstekniske zoner") and are only to be used in connection with the screening of contaminated sites under the Danish Soil Act (Miljøstyrelsen, n.d.b). The Danish Environmental Protection Agency defines the dimensions of the calculated mixing zones in streams as 10 times the width of the stream, up to a maximal distance of 100 m from the upstream point of the discharge area. It is required that the concentration of pollutant downstream the boundary of this calculated mixing zone complies with the relevant EQS (Miljøstyrelsen 2017, 2018). The calculated mixing zones are only applicable for soil contaminations without an “owner” (“herreløse forureninger”). They are solely aimed for identification of soil contaminations potentially posing a risk to surface waters. The dilution and mixing conditions in streams in this report are compared to the calculated mixing zones as defined by the Danish Environmental Protection Agency for contaminated sites under the Danish Soil Act. As the dimensions of mixing zones and calculated mixing zones are identical, the comparisons between the behaviour of contaminants from landfill leachate plumes with the size of calculated mixing zones are considered representative of both regulative systems in the current report.

3.2 Fully mixed condition in stream

The point of fully mixed conditions defines the location along the stream where the pollutant and associated concentration denoted C_{mix} are completely mixed. This point is of particular interest as in fully mixed conditions the pollutant concentration should be constant in any given point sampled in a given transverse section of the stream downstream a distance L_{mix}.

There is no legal definition of fully mixed conditions. The Danish EPA risk assessment tool for screening of contaminated sites posing a risk to surface stream water used the formulation by Fisher (1979) for the calculation of the distance of fully mixed condition L_{mix} and assess the concentration at that particular distance as C_{mix} (Miljøstyrelsen, 2014c):

$$L_{mix} = \frac{0.4QW}{0.3d^2\sqrt{gdS}} \qquad \text{Eq. (1)}$$

With *Q:* flow rate [L^3/T], *W:* width of the stream [L], *d:* the depth [L], *S:* the slope [-]. L_{mix} is in this formula defined from the downstream edge of the plume. This formula is nevertheless adapted only to point sources (contaminated sites of limited width in the flow direction) and is only an approximation.

3.3 Contaminant plume from landfills

This calculation (Eq. 1) is however difficult to apply to contaminant plumes from landfills, with plume widths up to several hundred meters and in the order of magnitude of L_{mix} (Miljøstyrelsen, 2014d; 2019). Indeed, the mixing process for such large plumes may already occur within the stream stretch where the plume is discharging, i.e. the contaminant can already be fully mixed before the downstream edge of the plume (between X=0 and X=W_{plume} in Figure 3 or calculation example in Appendix 5). Therefore, a more adequate definition also by Fisher (1979) and suitable for large plumes will be used in this report. If the concentration is known anywhere in the stream, then the fully mixed condition is reached when in a given cross section, the concentration values are almost constant, i.e. close to the average concentration typically in a 5% large interval:

$$C(L_{mix}, y_i) \in [\overline{C(L_{mix}, y)} +/- 2.5\%] \qquad \text{Eq. (2)}$$

This value of L_{mix} is defined from where the contaminant starts seeping into the stream, i.e. the upstream edge of the plume. Through this report, the concentration evaluated/measured at the downstream edge of this mixing zone will be named as C_{mz}.

The other relevant concentration quantities, i.e. the maximum concentration C_{max} and the fully mixed concentration C_{mix} are presented in Figure 3.

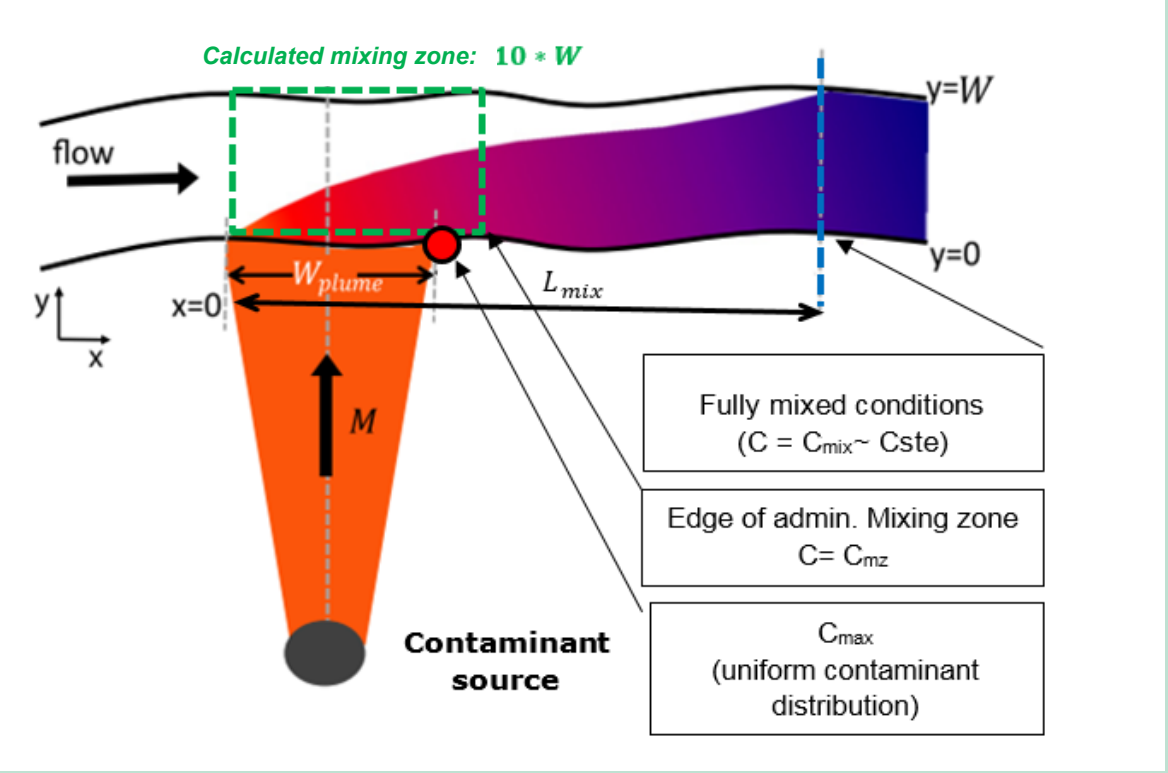


FIGURE 3. Schematic figure with relevant quantities for the dilution and mixing of a large uniform leachate plume in a stream, adapted from Miljøstyrelsen (2014b). Calculated mixing zone (dash green) and fully mixed conditions (dash blue) are shown. L_{mix} is here defined from the upstream point of the plume discharge, i.e. the same origin as the calculated mixing zone to facilitate the comparison. C_{mix} is evaluated at the distance L_{mix}, while C_{mz} is evaluated at the downstream edge of the calculated mixing zone. Cmax is plotted for a uniform distribution of contaminant in the plume.

4. Strategy for the assessment of contaminant concentration in streams from landfill leachate

4.1 General approach for the evaluation of contaminant concentration in streams

The model for dilution and mixing of contaminants in streams employed for this study is a continuous development of a 2D analytical steady state model including transport, dispersion, as well as a possible volatilization of the investigated contaminants (Aisopou et al., 2015). The contaminant plume is modelled as a diffuse source given as a contaminant mass discharge seeping from either the bank or the streambed over a certain area corresponding to the plume. The water balance is incomplete as the groundwater seeping is assumed negligible compared to the stream water flow in order to solve the equation (Miljøstyrelsen, 2014d; Lemaire, 2016). For this study, and in the general context of contaminant leaching from landfills, a conservative model will be built for the dilution/mixing in the streams, i.e. no volatilization, sorption, precipitation/dissolution nor degradation will occur from the point where the contaminant plume seeps into the stream (see section 4.5 for details).

4.2 Link and data exchange between models

The leachate quantity and the compound concentrations with time from the source term model are directly used as input for a transport model (e.g. GrundRisk Landfill, Miljøstyrelsen, 2019).The contaminant input required in the dilution/mixing model is a steady state contaminant mass discharge. The transport model provides a time-dependent contaminant mass discharge on a yearly basis over a 500-year period. As the variation of concentration induced by the time variation of the contaminant mass discharge in a stream are in the order of minute/hour time scale (dependent on the stream flow and size), the yearly variations of contaminant mass discharge from the transport model can be seen as very slow and therefore assumed constant from the stream perspective. Consequently, the contaminant mass discharge computed on a yearly basis by the transport model can be employed as a steady state input in the stream model. A list of all required input parameters for the dilution/mixing model is given in Appendix 2.

4.3 Contaminants considered for the study

The compounds found in landfill leachates are numerous, and their fate in groundwater and stream water can vary from one compound to the next. A list of problematic compounds based on average estimate of leachate concentrations and associated EQS in groundwater and surface water was proposed for the development of the source strength model (Miljøstyrelsen, 2018a). A representative selection was performed to provide relevant case studies for the evaluation of the contaminant mixing and dilution in streams. The selection was carried out using the following approach:

- The compound list contains at least one nutrient, one metal ion, one macroion, one xenobiotic organic contaminant, i.e. compounds with different chemical properties and fate.
- Comparison of 90% percentile concentration in leachates to the relevant EQS (spreadsheet prepared as part of Miljøstyrelsen, 2018a). A maximum dilution factor of 5 between the leachate concentration and the final concentration in the stream complying with the EQS is

required or the substance is screened as a potential threat and possibly selected. The value for the dilution factor was selected in Miljøstyrelsen (2018a).

- Comparison of 90th percentile concentration to a measured concentration at the three landfills considered for this project: Faaborg, Tandskov and Hørløkke (Miljøstyrelsen 2019), and corresponding concentration plot in Appendix 6. Any significant discrepancy between the measured concentrations and the 90th percentile concentrations in landfills, leading to higher dilution factor, is evaluated.

This approach resulted in the selection of ammonium as a nutrient, chloride as a macroion, nickel as a metal and benzene as an organic contaminant (Table 1). Iron was added to the list, because it was identified as an important landfill compound for assessment of surface water quality (Miljøstyrelsen, 2014e). Iron is assumed to be present as ferrous iron (Fe^{2+}), but it will most likely be oxidized to ferric iron (Fe^{3+}) in the stream and maybe precipitate in the streambed as iron(oxy)hydroxide.

TABLE 1. Selected compounds for the evaluation of contaminant mixing in streams
Based on list from Miljøstyrelsen (2018a) and estimates/measurement at landfills from the same report

Compound	Type	EQS [µg/L]	Reference
Ammonium (NH_4^+)	Nutrient, cation	50 (ammonium-N)** 11 300 (Total-N)*	(Miljøministeriet, 2018)
Chloride (Cl^-)	Salt, macroion	250 000 **	(Miljøministeriet, 2018)
Nickel (Ni^{2+})	Metal	4	(Miljøministeriet, 2017)
Iron (Fe^{2+})	Metal	100**	(Miljøministeriet, 2018)
Benzene	BTEX	10	(Miljøministeriet, 2017)

* The requirement on total-N is based on the molar summation of NH_4^+/NO_3^- requirement combined
**: No relevant EQS. The drinking water criterion is used.

It is important to highlight that for some compounds (marked by ** in Table 1), the EQS for the contamination in streams and in general surface water are non-existent. For these particular cases, the EQS for groundwater and drinking water are used (Miljøministeriet, 2018). These criteria are adapted and developed for human health and not for aquatic life.

4.4 Definition of the stream configuration

The investigation of the contamination from contaminated sites to stream water uses a categorization of the streams in 3 groups from small to large (Miljøstyrelsen, 2014d). For consistency purposes, a similar categorization will be used for the contamination from landfill leachate plumes.

In total, six stream configurations are created with two extreme cases for each category based on 10 and 90% percentile flow rate. These minimum and maximum flow rates are associated to minimum and maximum width of the stream respectively. The flow rate values for the different stream categories were updated recently compared to the initial classification (Miljøstyrelsen, 2015). In the absence of well-defined configuration and data, a realistic default value for the slope is defined as 0.5‰ for each of the configurations. The associated depth for the different stream configurations is then assessed by using Manning's equation for open-channel flow (see Appendix 8 for detailed methodology). The different stream parameters required for the mixing dilution model are given in Table 2.

TABLE 2. Main parameters for the stream configuration based on classification from Miljøstyrelsen (2014d), flow rate from Miljøstyrelsen (2015). Depth and slope calculated by standard open channel flow calculation (Appendix 8).

	Small stream		Medium stream		Large stream	
	Low limit (case 1)	High limit (case 2)	Low limit (case 3)	High limit (case 4)	Low limit (case 5)	High limit (case 6)
Width [m]	1	2	2	10	10	15
Flow rate [m^3/s]	0.01	3**	0.08	1	2	8
Depth [m]	0.2	1.1	0.5	0.8	1.25	2.3
Slope [-]	0.0005	0.01**	0.0005	0.0005	0.0005	0.0005

** The slope needed to be increased to be able to assess a realistic configuration of small stream with high flow. The maximum flow rate is still less than the 90% percentile presented in Miljøstyrelsen (2015), and correspond to extremely high slope or smooth and deep narrow channel.

4.5 Required parameters for the evaluation of contaminant concentration in streams

In this section some parameters and chemical/environmental data are reviewed, which influences the mixing and resulting concentrations of contaminants in stream water. It is also reviewed how these parameters should be handled with the mixing/dilution model in the risk assessment of streams.

4.5.1 General model parameters

In stream waters, the mixing of contaminant is mostly caused by mechanical dispersion processes induced by flow turbulences. These turbulences are analytically described by a mixing coefficient ξ proportional to a dispersion constant ξ_o and flow velocity data of the form (Fischer, 1979):

$$\xi = \xi_o * d * u^* \qquad \text{Eq. (3)}$$

With *d* depth [m], and *u** shear velocity [m/s] and ξ_o [-]. This dispersion constant ξ_o is an empirical parameter depending on stream/channel and will vary with stream morphology. It will for example increase in case of meandering of the stream, sharp bends or increased roughness of the streambed resulting in faster full mixing of the compound in stream (Rutherford, 1994). For the current study, all streams will be considered as straight and consequently the dispersion constants equal to the values already used for the assessment of the contamination in stream waters from contaminated sites (Miljøstyrelsen, 2014d and Appendix 2 and 3). These values are likely to underestimate the actual mixing, where meandering and relatively rough streambed can occur (which will increase mixing). Thereby, the mixing length will be overestimated. Experience and literature on the effect of meandering stream and roughness compared to a straight stretch of stream is limited. The use of the mixing/dilution model and rough calculation indicate possible reduction of 50 to 75% of the mixing length (calculation using transverse mixing coefficient $\xi_{o,t}$=0.8, Fisher, 1979).

4.5.2 Contaminant inherent properties

The main chemical characteristics of a given compound will influence its concentration when discharged in the stream environment. Volatilization is a first characteristic that can strongly influence the pollutant concentration in the stream, as a volatile compound can be transferred from the stream water to the surrounding air. Sorption of the compounds to clay and organic matter, e.g. metals, can also reduce the contaminant concentration, as well as possible degradation (biotic or abiotic).

These characteristics are dependent on both stream/contaminant and general environmental variables and a conservative approach is here privileged for a general screening method, i.e. volatilization, sorption, precipitation/dissolution, and degradation are not considered. The assumptions are partially tested for volatilization, where the effect will be minor within short distances and relatively deep stream, i.e. with depth > 1 m (Aisopou et al., 2015). Similarly the effect of degradation is expected to be small over short distances because of the small retention time in streams. Sorption and precipitation processes may result in a relevant reduction of the contaminant mass discharge when the groundwater reaches the stream and flow through the interface groundwater/stream water known as hyporheic zone. Sorption to sediments, especially for metals, can also result in a reduction of the compounds found in the stream water.

4.5.3 Contaminant distribution and dispersion in the leachate plume

The width and contaminant distribution in the leachate plume discharging to the stream is dependent on the dimension of the contaminant source, its general orientation with respect to groundwater flow, and its spread during the transport phase.

For the transport model (in this case GrundRisk Landfill) the width of the source is directly equal to the width of the landfill as assessed in the source strength model (Miljøstyrelsen, 2019). Furthermore, the source strength model assumes a uniform distribution of the contaminant leaching from the source area and consequently, a uniform contaminant discharge into the aquifer is used for the transport model (GrundRisk Landfill in this case or other).

When the plume reached the stream, its width and contaminant distribution may have been modified by the dispersion into the aquifer. Assuming no loss of contaminant during the groundwater transport and a full contaminant discharge into the surface water, the further from the surface water the source is, the wider and more spread is the plume. This spread effect and its influence on the contaminant dilution/mixing in stream is here examined.

A simulation is carried out assuming a contamination into a stream originating from a source located at different distances to quantify the dispersion effect due to the groundwater transport on mixing length, fully mixed concentration and maximum concentration in the stream. Two sizes of sources are considered. A fictive narrow source of 20 m and a realistic large source of 170 m. wide (Based on the estimation of Tandskov landfill cells, Miljøstyrelsen, 2019). For these two sources, two configurations are tested: the plume width is identical to the source width, i.e. the dispersion is negligible, or the dispersion is taken into account (and therefore the plume width is larger than the source width). The parameters for the transport model are given in Appendix 3.

Figure 5 and Figure 6 present the contaminant distribution in the transverse direction of the plume at different distances from the source. In Table 3 is given the relative increase of plume width due to spreading up to a maximum distance of 500 m between the source and the stream (the plume width is defined as containing 99% of the contaminant mass).

The simulation results show that the dispersion effect is relatively small and the contaminant distribution is relatively unaltered for a large plume: after 500 m., the plume width is app. 1% larger than the source and still uniformly distributed, as seen in Figure 6. On the other hand, the relative increase of the plume width due to the dispersion effect for a narrow plume of 20 m. is not negligible with a relative increase of 33% of its size, and a pollutant distribution tending towards a Gaussian shaped (Figure 5). It is important to notice such a narrow plume was used for illustration purpose and are not expected for contaminant plume leaching from landfills.

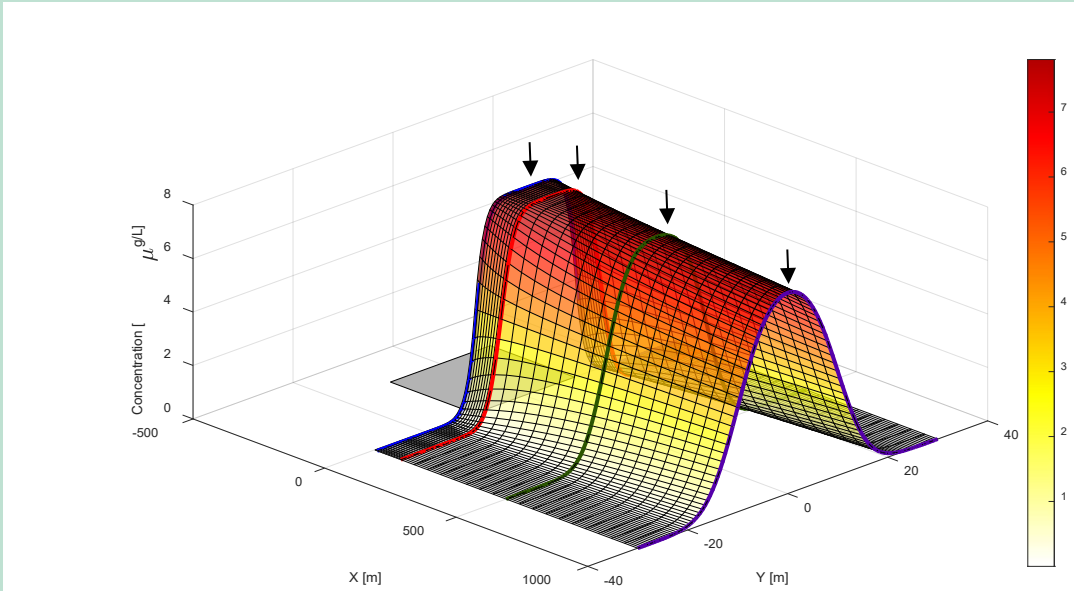


FIGURE 4. Over Surface plot illustrating the contaminant concentration distribution and spread during groundwater transport distance. X: direction of the groundwater flow, Y: transverse to the flow, Z: Concentration value. Landfill source location shown in grey, transverse sections of interest marked and plotted in Figure 5 below.

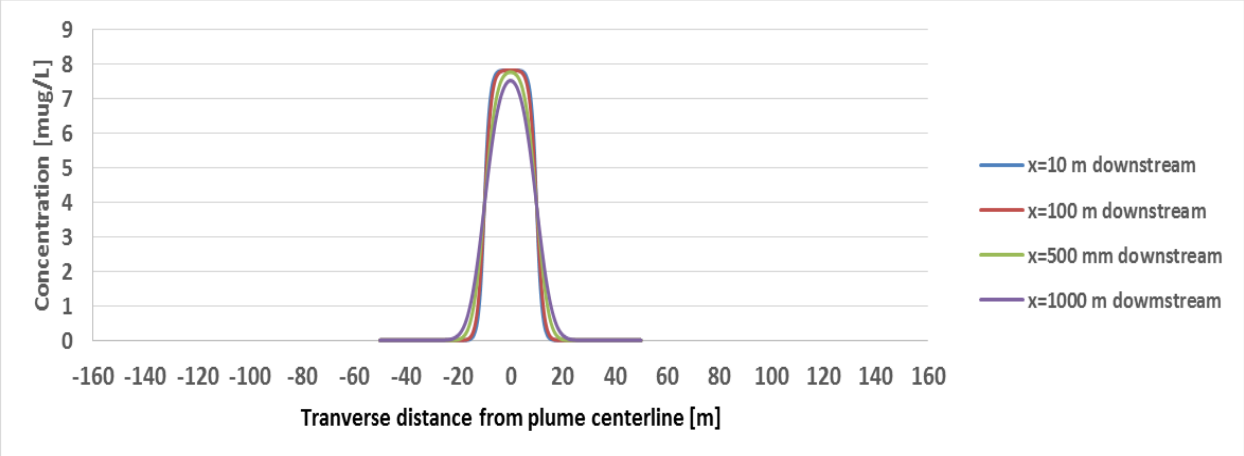


FIGURE 5. Contaminant distribution (transverse from plume) at different distances downstream from the source. Example of a narrow plume 20 m wide with uniform contaminant distribution in the source area. Transport model parameters in Appendix 3.

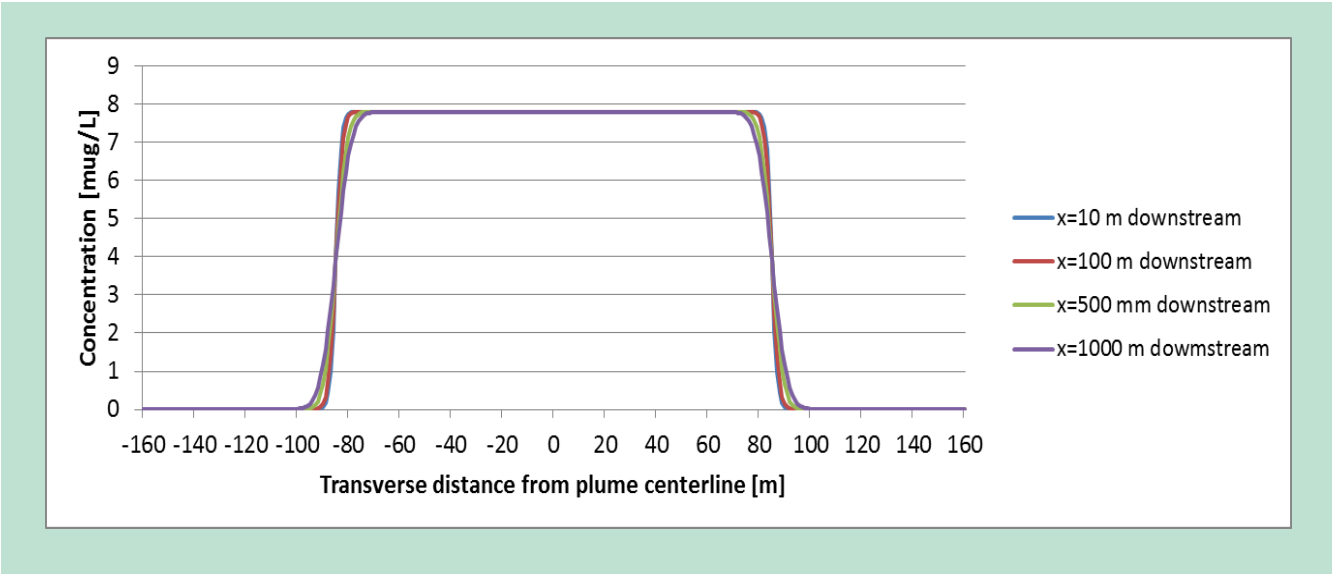


FIGURE 6. Contaminant distribution (transverse from plume) at different distances downstream from the source. Example of a large plume 170 m wide with uniform contaminant distribution in the source area. Transport model parameters in Appendix 3.

TABLE 3. Evolution of plume width at different distances downstream the source. The plume width is defined as containing 99% of the contaminant mass released from the source).

Distance downstream source	Source width = 20 m		Source width = 170 m	
	Plume width [m]	Relative increase/ source width [%]	Plume width [m]	Relative increase/ source width [%]
X= 10 m	24	+20	170	< 1
X= 100 m	26	+30	171	< 1
X = 500 m	30	+50	172	+1
X=1000 m	36	+80	174	+2

The repercussions of these variations are evaluated on the contaminant concentration C_{mix} and C_{max} into the stream. The variations of C_{mix} are shown in Figure 7 below for the large plume of 170 m (The other results are gathered in Appendix 3), The variation of plume width by dispersion during the groundwater transport has a negligible effect on the fully mixed conditions and maximum concentrations found in the stream, for both the tested stream configuration, the size of the plume and the distribution evolution due to spreading (order of magnitude of a few %, Appendix 3). As the overall mass of contaminant is unchanged the resulting mixed concentrations in the stream are unaltered.

In the light of these results, it is concluded that the dispersion effect and change in contaminant distribution on the resulting concentration and mixing in stream is limited as long as the heterogeneity in the source distribution is not accounted for in the source strength / transport model (Miljøstyrelsen, 2018b). Consequently, the dispersion effect is neglected when evaluating the mixing of large leachate plume in streams and the contaminant plume can be assumed uniformly distributed over a width equal to the source width.

4.5.4 Influence of the discharge location - bank versus streambed

In this section, the effect of the discharge location of the leachate plume on the contaminant mixing and dilution in stream is examined. The stream case 4 (medium stream, W = 10 m, Q=1 m^3/s) is employed as a general illustrative case (Table 2). A unit discharge of 1 kg/y over

an arbitrary and large 200 m wide plume is used for the contaminant discharge input, and only the discharge location, i.e. from the bank or half a streambed, is modified between the two mixing/dilution simulations. The 200 m large plume is chosen as a representative plume width, based on the source/landfill area distribution presented by Miljøstyrelsen (2014e) and the actual size of landfill sites used for testing of the models (Miljøstyrelsen, 2019).

Figure 7 presents a contour map of the contaminant mixing in the stream, and where maximum and fully mixed concentrations are achieved. Quantitative values are given in Table 4 below.

TABLE 4. Evolution of fully mixed concentration and distance and maximum concentration max. for different seepage areas in the stream. Stream case 4, see Table 2.

Discharge area	L_{mix} [m]	C_{max} [µg/L]	C_{mix} [µg/L]
Streambed (1/2)	451	4.5	3.1
Bank	489	6.7	3.1

The simulation results show that the fully mixed conditions as described by eq. (2) is achieved at a shorter distance L_{mix} when the plume is discharged from the streambed compared to the bank (Figure 7). The maximum concentration C_{max} varies between the two simulations and is higher in the case of a bank as a result of the contaminant distribution. These results can be generalized to all stream configurations when a uniform constant distribution is applied. The fully mixed concentration C_{mix} is equal for both scenarios, as the contaminant mass discharge and stream parameters are identical in these two simulations. The point of maximum concentration is for both simulations found at the downstream edge of the leachate plume where the contaminants are fully discharged into the stream. These results are in accordance with what was already observed and reported by Miljøstyrelsen (2014d).

Ultimately, a contaminant discharge from the bank will be chosen as it will give a conservative estimate of the mixing conditions and the maximum concentration. The mixing length will be longer, and at the distance of fully mixed conditions, the concentration will be similar for the two situations.

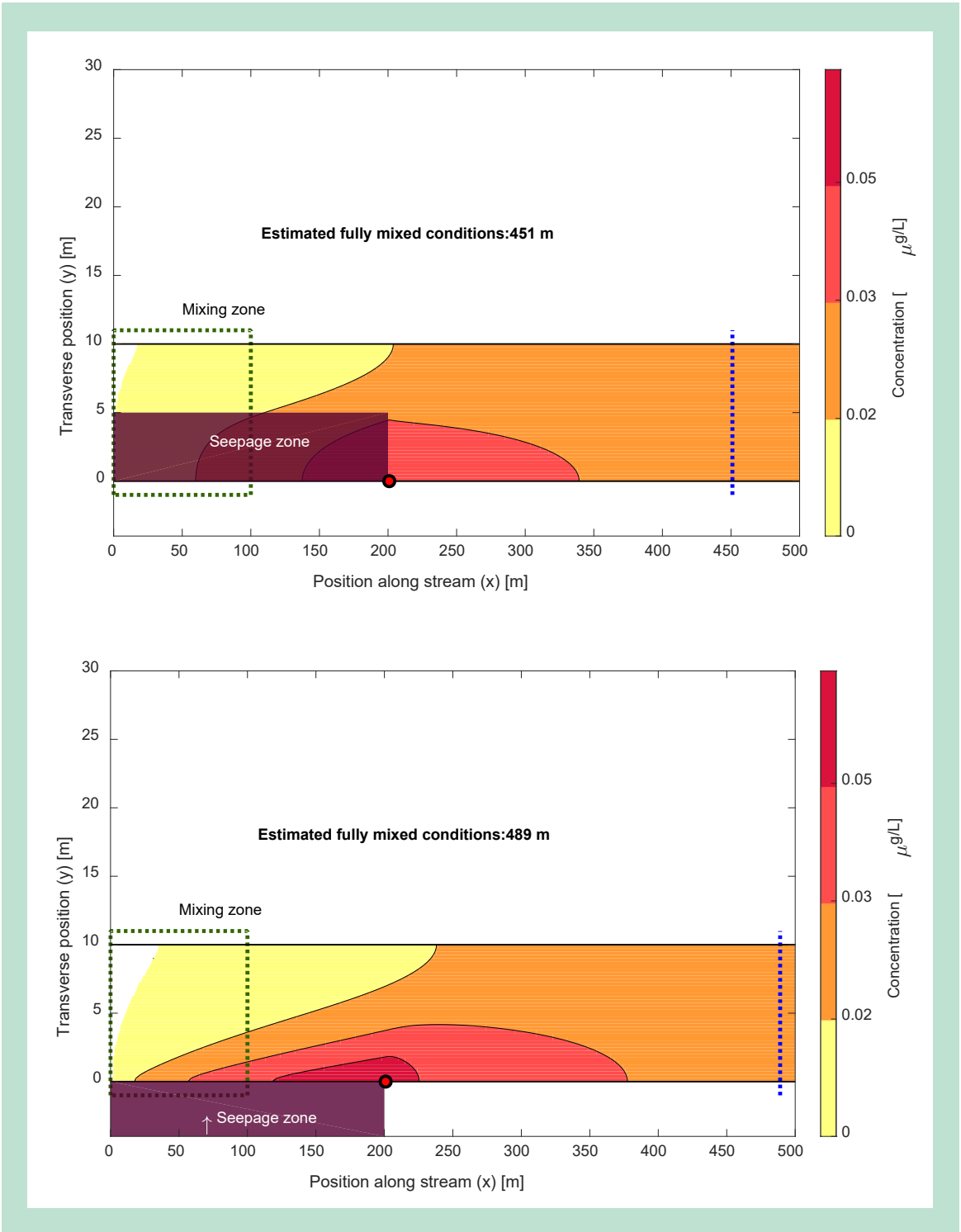


FIGURE 7. Evolution of the contaminant concentration in stream configuration 4 (W= 10 m, Q = 1 m3/s), plan view. Upper figure: seepage from ½ streambed. Lower figure: seepage from the bank. Plume 200 m large, with a discharge J = 1kg/y uniformly distributed. Blue line: fully mixed conditions defined by eq. (2). Green line: Calculated mixing zone. Red marker: maximum concentration C_{max}.

4.6 Summary of methodology for the assessment of contaminant concentration in stream

The estimation of contaminant concentration in stream waters originating from a landfill leachate plume can be handled by use of an analytical mixing/dilution model. This model interfaces easily with a transport model of the contaminant in the aquifer (e.g. GrundRisk Landfill) by use of the contaminant mass discharge quantity – output of the transport model.

Several investigations were performed to propose a robust methodology applicable to the numerous cases encountered both in terms of leachate plumes and streams:

- The mixing/dilution model is applied to straight streams which is conservative in terms of mixing distance. In total, 6 configurations corresponding to small, medium and large streams in Denmark were determined.
- The resulting concentrations in stream waters are sensitive to possible volatilization, sorption and degradation properties of the investigated compounds. Considering the variety of compounds possibly leaching, a conservative approach assuming no transfer nor immobilization nor degradation of the compound is privileged.
- During the contaminant transport phase in the aquifer, the dispersion spreads the contaminant plume and the contaminant distribution is modified, depending on the source/stream location. The transport simulations show that uniform or Gaussian-shaped distributions of the leachate plume are expected as long as the source strength/transport model uses a homogeneous source distribution. The effect of this spreading and change in distribution has nevertheless little influence on the relevant quantity in stream waters, i.e. mixing distance, fully mixed concentration and maximum concentration for leachate plumes that are in the order of hundred meters large (Appendix 3, section 4.5.3). Therefore this spreading effect can be neglected and the leachate plume width will be set equal to the source width defined in the transport/source strength model for the calculation of mixing/dilution in stream.
- Once the leachate plume reaches the stream, the discharge can occur through the bank and/or streambed depending on local hydrogeological conditions. The discharge from the bank is seen as a conservative assumption with respect to the point of mixing conditions and the maximum concentration.

5. Assessment of contaminant mixing in streams

5.1 Evaluation of contaminant concentration and mixing for the selected stream configurations

In this section, a visualization of a “standard” plume is proposed for all the stream configurations defined in section 4.4. Following the guidelines defined in section 4.6, the plume is assumed to discharge from the stream bank uniformly, and a standard (normalized) contaminant mass discharge of 1 kg/y is considered for later scaling purpose.

Two plume widths are considered: a representative landfill leachate plume of 200 m and a theoretical narrow plume of 20 m to better assess the effect of plume width (although this situation is unusual for landfills). For each case and configuration, the mixing length is evaluated as defined by Equation 2. Additionally, a comparison of the maximum concentration at the calculated mixing zone limit (denoted as C_{mz} in this report, see Figure 3), the overall maximum concentration C_{max} and the fully mixed concentration C_{mix} is proposed. Associated contour maps of the contaminant concentration along the stream for all configurations are presented in Appendix 4. The contour map for the mixing in a small stream (configuration 2, W= 2m and Q=3 m^3/s) is shown below as an example, with the evolution of concentration along the stream bank.

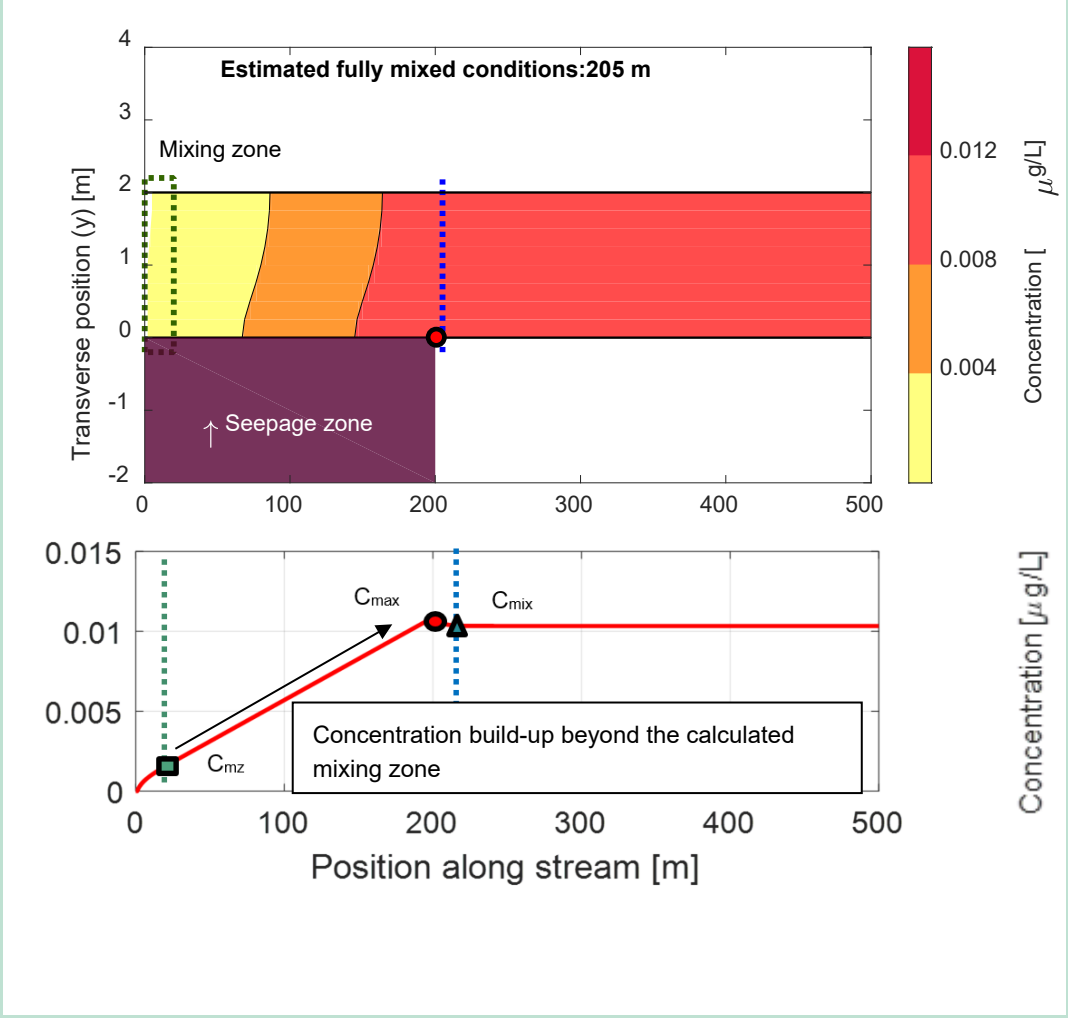


FIGURE 8. Upper graph: Calculation result of a leachate plume mixing in a small stream – stream configuration 2 (W=2 m, Q = 3m^3/s). Plume 200 m large, with a discharge J = 1kg/y uniformly distributed. Blue line: fully mixed conditions defined by eq. (2). Green line: Calculated mixing zone.
Lower graph: Evolution of concentration along the bank where the plume discharges showing C_{max} (red round marker), C_{mz} (blue square marker) and C_{mix} (triangle marker). A significant amount of contaminant seeps into the stream downstream of the mixing zone.

For all stream configurations the fully mixed conditions are achieved far beyond the limit of the calculated mixing zone as defined by the Danish Environmental Protection Agency, both for the large and narrow plumes (Figure 9 and Appendix 4 for the narrow plume). The mixing distance varies for all configurations and is dependent on stream geometry, flow rate and the plume width for a given mass discharge that influences the build-up of the contaminant in the stream.

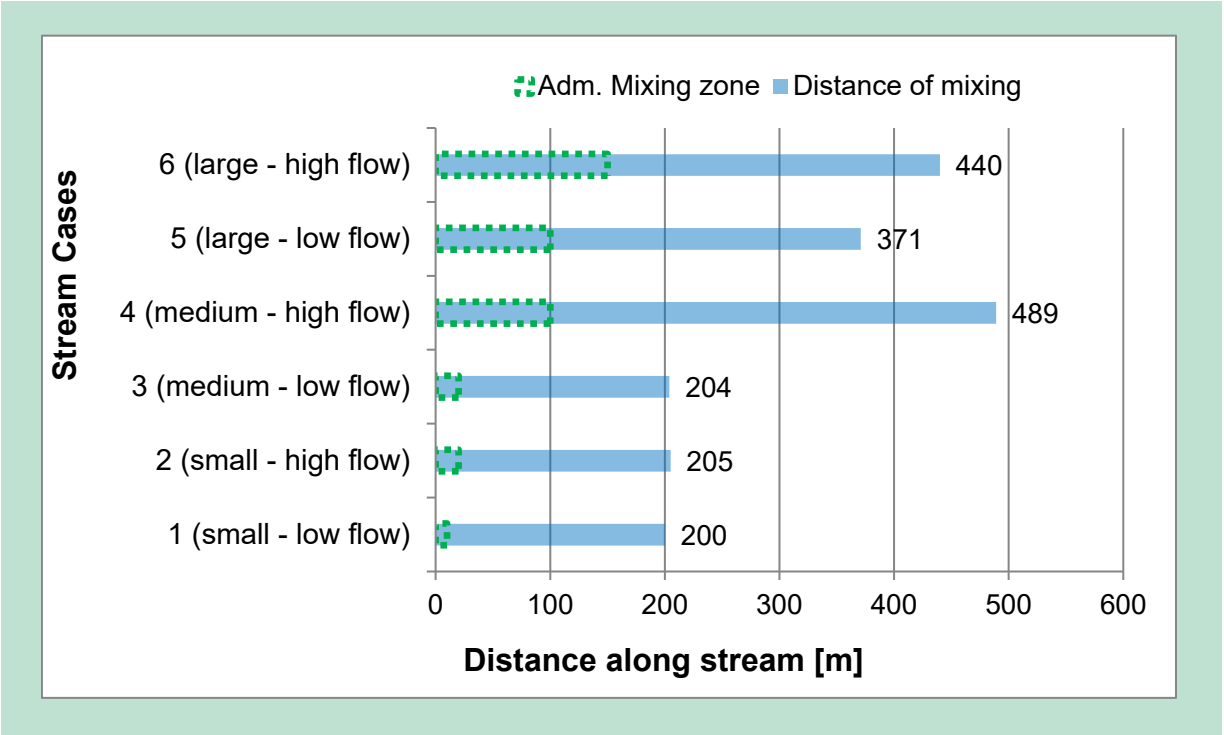


FIGURE 9. Evaluation of fully mixed conditions defined in eq. (2) for the different stream cases and comparison to the calculated (administrative) mixing zone definition (section 3.1). Leachate plume: 200 m wide.

All estimated concentration values are significantly different between the cases due to the variation in flow rate and resulting dilution of the contaminant between the different stream configurations. The highest concentrations are found in the small stream configuration 1 (W=1m, Q= 0.01 m^3/s) corresponding to the lowest possible flow rate and lowest dilution. The estimated concentrations highlight that the maximum concentration at the limit of the calculated mixing zone C_{mz} is lower than the actual maximum concentration C_{max} encountered in the stream for all the tested configurations, and for both large and narrow plumes. For the 200 m wide plume, these concentrations vary from a minimum factor 1.4 (stream configuration 6) to a factor 16 (stream configuration 1). This concentration C_{mz} is lower than the maximum concentration C_{max} as the calculated mixing zone ends far before the overall width of the leachate plume, i.e. not all contaminant mass has entered the stream (see Figure 8 – lower graph). The fully mixed concentration C_{mix} is also less than C_{max} due to on-going mixing downstream and spread of the contaminant throughout the section, but limited to one order of magnitude (factor 2) for the large plumes.

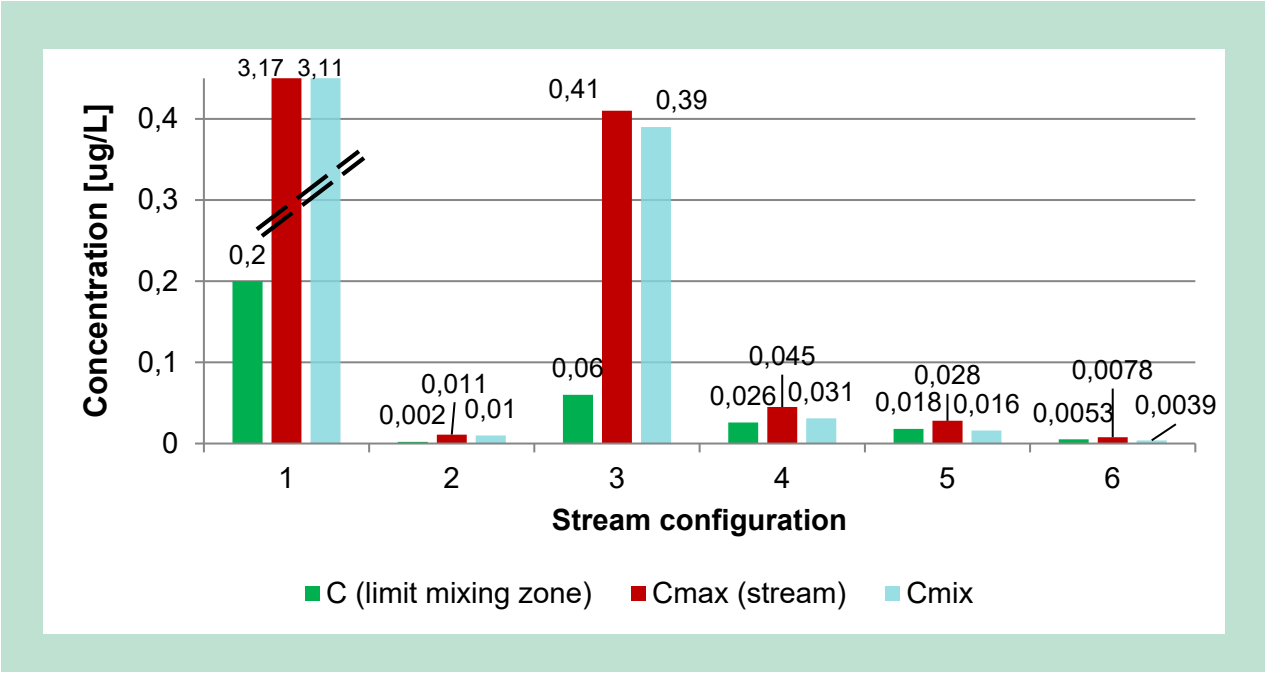


FIGURE 10. Comparison of the maximum concentration at the limit of the calculated mixing zone C_{mz}. Maximum concentration in the stream C_{max}, and fully mixed concentration C_{mix}. Plume width 200 m, discharge 1 kg/y. Note: The dashed line shows the highest and lowest values in configuration 1.

5.2 Generalization of results to random stream dimensions

An attempt to generalize the observations presented for the six chosen configurations is proposed in Appendix 9 by use of a Monte Carlo simulation for the three stream categories small, medium and large. The results of these simulations are in agreement with the results given in section 5.1 for selected configurations and are summarized below:

- The longest mixing distances are found for the largest streams where width and flow rates are the largest (Table 5). The average mixing length for the simulation of large streams is 463 m from the upstream point of the plume, which corresponds to approximately 36 times the width of the large stream dataset (this factor 36 can be compared to the factor 10 suggested by the European law, section 3.1).
- For almost all large and medium stream configurations tested, the fully mixed conditions are achieved beyond the limit of the calculated mixing zone as defined by the Danish Environmental Protection Agency) (> 99 to 100% of all configurations). For small streams, a significant number of simulations outline mixing distances beyond the calculated mixing zone (around 86%).
- While the maximum and fully mixed concentrations can be compared and are within one order of magnitude for all stream categories, the concentration at the edge of the calculated mixing zone C_{mz} is significantly lower that the fully mixed one C_{mix} for the small streams and is related to the limited size of the calculated mixing zone (maximum of 10 times stream width) compared to the plume width typically several hundred meters large (Figure 11 below). No specific trend can be inferred for the medium and large streams with respect to the two quantities C_{mz} and C_{mix}

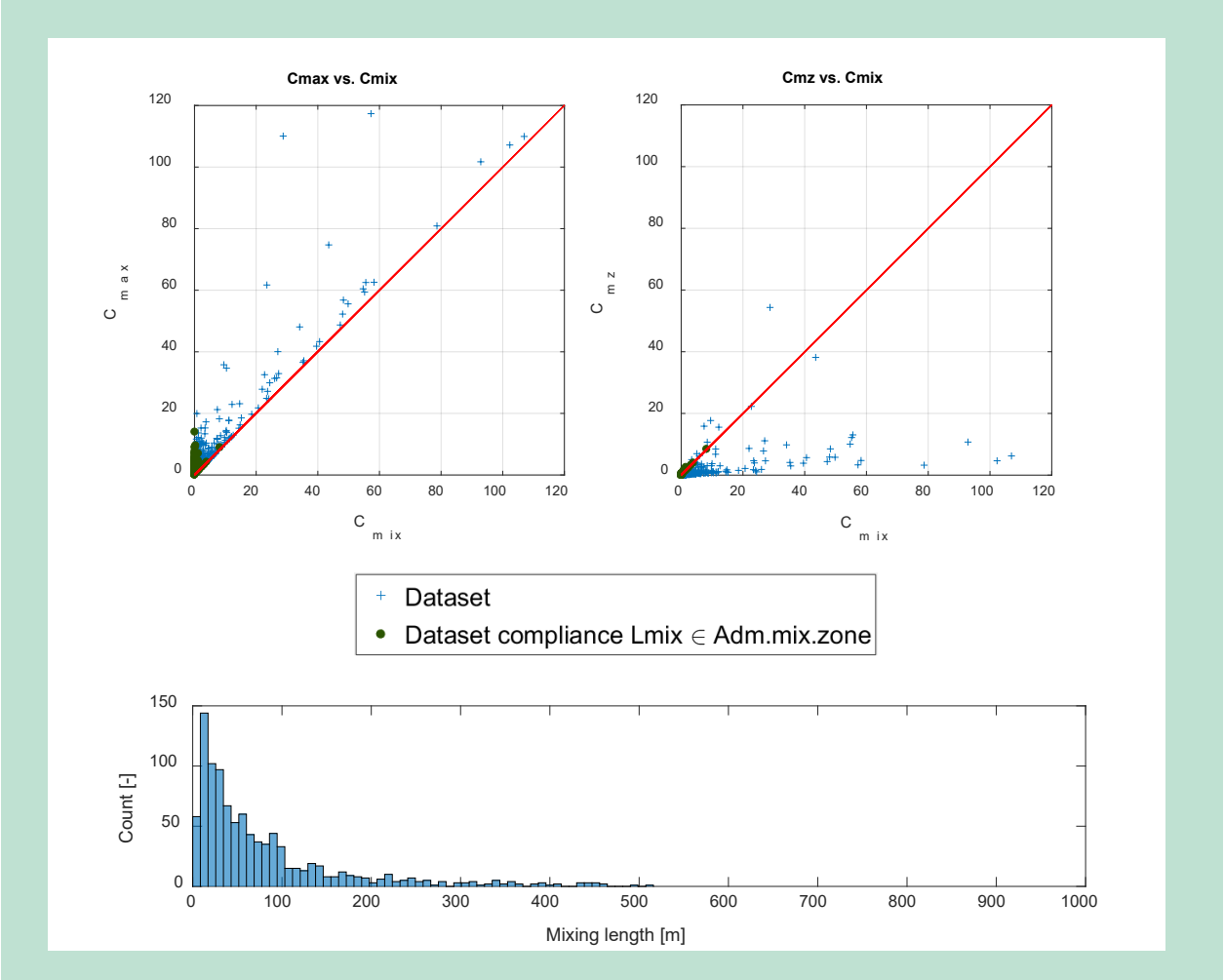


FIGURE 11. MC simulation results for small streams: Evolution of C_{max} compared to C_{mix}, and max. concentration at the limit of the calculated mixing zone C_{mz} compared to C_{mix}. Green marker shows a configuration where Lmix is achieved within the calculated mixing zone. Lower figure: histogram of distribution for the mixing length.

TABLE 5. Summary of mixing length values assessed by Monte Carlo simulation for the three categories of streams. Average and quantile values, and ratio Lmix/stream width.

Stream configuration	L_{mix}		L_{mix}/W	
	Average [m]	Median (25/75th percentile) [m]	Average [-]	Median (25/75th percentile) [-]
Small	79	48 (20,98)	49	28 (13,61)
Medium	379	366 (208,516)	62	61 (42,80)
Large	463	463 (350,570)	36	36 (25, 45)

This generalization combined with the selected representative datasets suggests that the definition of the calculated mixing zone as currently defined by the Danish Environmental Protection Agency will be a challenge to landfill leachate plumes. The concentrations at the limit of this zone are not entirely fully mixed and can underestimate the fully mixed and maximum concentration found downstream of the plume.

6. Evaluation of selected contaminant concentrations in streams at three Danish landfills

The previous section used normalized leachate plumes for illustrative purpose of the contaminant mixing in streams. In this section, the model is applied to the landfill leachate plume originating from the three selected landfills (Tandskov, Faaborg and Hørløkke) used as examples. The investigated compounds are ammonium, chloride, nickel and iron (ferrous). The estimated mixed concentrations in streams are compared to the relevant EQS presented in section 4.3 (Table 1).

The output contaminant mass discharges estimated from the transport model are used in combination with the assumptions presented in section 4.6 to give quantitative values of concentrations in the defined stream configurations and reflect on possible/expected issues.

6.1 Tandskov

Tandskov is a landfill close to Silkeborg, Jylland. It is made of several cells, some with leachate control and the oldest without. A short description of the site, geology and hydrology can be found in Miljøstyrelsen (2019). The contaminant mass discharge of the selected compounds ammonium and chloride are given in Table 6. The values for these two compounds were computed at a POC = 100 m over a 500 year period by use of the transport model (GrundRisk landfill) and source term model. No degradation of these compounds is taking place in the aquifer. The simulation of dilution into a stream is performed using the maximum value of contaminant mass discharge computed for both compounds as a full discharge into the streams (see red circle in Figure 12).

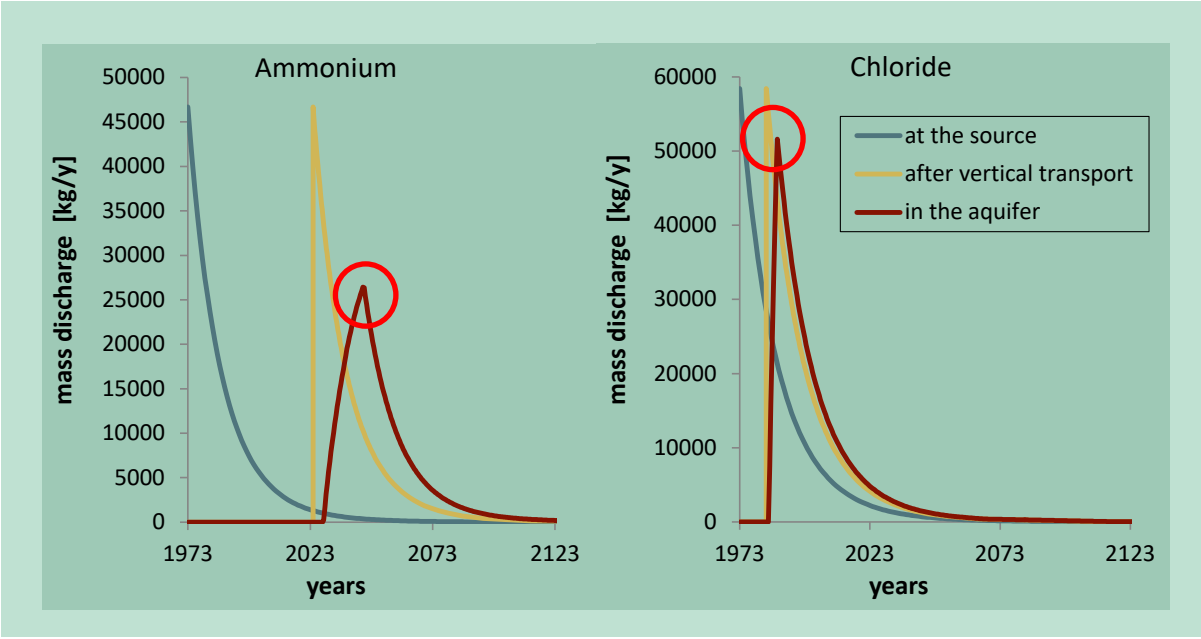


FIGURE 12. Visualization of the maximum Contaminant Mass Discharge (CMD) for ammonium and chloride at Tandskov landfill. Output parameter from the transport model (GrundRisk Landfill) used as input in the mixing/dilution model. Figure retrieved from Miljøstyrelsen (2019).

The results presented below are correct under the assumptions presented in Section 4.6, i.e. the stream is located at a distance of maximum 500 m from the landfill, no degradation, sorption nor volatilization occur for any of the substances in the stream. For the current simulation, only the unit 1 of the landfill (uncontrolled without membrane and leachate collection system) is taken into account as it was assessed as the dominant source of contamination for the selected compounds (Miljøstyrelsen, 2019). Stream configuration 1 (small stream, W=1 m, Q=0.01 m^3/s) and stream configuration 6 (large stream, W=15 m, Q=8 m^3/s) are investigated as worst and best scenario respectively corresponding to lowest and highest dilution of contamination in streams. Stream configuration 3 is also given for a medium stream category.

TABLE 6. Required parameters for assessment of contaminant concentration in streams at Tandskov Landfill. POC = 100 m downstream in the aquifer. All data come from the transport model (Miljøstyrelsen, 2019). All stream parameters are defined in Table 2.

Parameters	Value	Comments
Plume width [m]	142	Unit 1 only, equal to source width
Contaminant mass discharge ammonium [kg/y]	25698*	Unit 1 only, POC at 100 m downstream
Contaminant mass discharge chloride [kg/y]	51599*	Unit 1 only, POC at 100 m downstream

* Extracted from the transport model output, see Figure 12.

TABLE 7. Estimated concentration in the selected stream case at the edge of the calculated mixing zone C_{mz}, max. concentration in stream C_{max} and fully mixed concentration C_{mix} for 2 selected compounds leaching from Tandskov landfill. Comparison to the requirements defined in Table 1.

Stream case	Ammonium – N* [mg/L]				Chloride [mg/L]			
	EQS	C_{mz}	C_{max}	C_{mix}	EQS	C_{mz}	C_{max}	C_{mix}
1 (W=1 m, Q=0.01 m^3/s)	0.05 (NH_4^+ -N) 11.3 (Total-N)	6.2	65.6	63.4	250	16.0	169.4	163.6
2 (W=2 m, Q=3 m^3/s)		0.027	0.228	0.210		0.115	0.588	0.545
3 (W=2 m, Q=0.08 m^3/s)		1.5	8.4	7.9		4.0	21.8	20.4
4		/	/	/		/	/	/
5		/	/	/		/	/	/
6 (W=15 m, Q=8 m^3/s)		0.153	0.187	0.080		0.397	0.483	0.204

/: Not calculated

*: The computation is performed in molar unit of ammonium and converted to kg N for comparison to requirements.

The estimated concentrations of chloride in the stream case 1 comply with the requirement established in Table 1, corresponding to the drinking water criterion (max. concentration, fully mixed and at the limit of the calculated mixing zone). Considering the conservative assumptions made and the fact that case 1 is the worst case scenario, it is expected that the concentration of chloride in all the other tested stream cases will comply with the associated requirement.

The concentration of ammonium (ammonium-N) is well above the relevant requirement when the dilution in stream configuration 1 is tested, and still exceeds in the stream configuration 6 corresponding to the most important dilution. However, ammonium will likely undergo nitrification in the stream environment, and comparison to the EQS for total nitrogen seems more appropriate. Under these conditions, the dilution offered by the stream case 1 is still not enough to comply with the requirement, but the requirement is fulfilled for large streams with higher dilution rates. It is therefore likely that the leachate plume of ammonium from Tandskov poses a threat to local small streams with low flow if present. It should be recalled that the requirement is based on drinking water criterion.

In terms of mixing length, the fully mixed conditions are achieved at approximately 144 m for the stream case 1 (Figure 13), i.e. at a relatively short distance downstream of the 142 m wide contaminant plume.

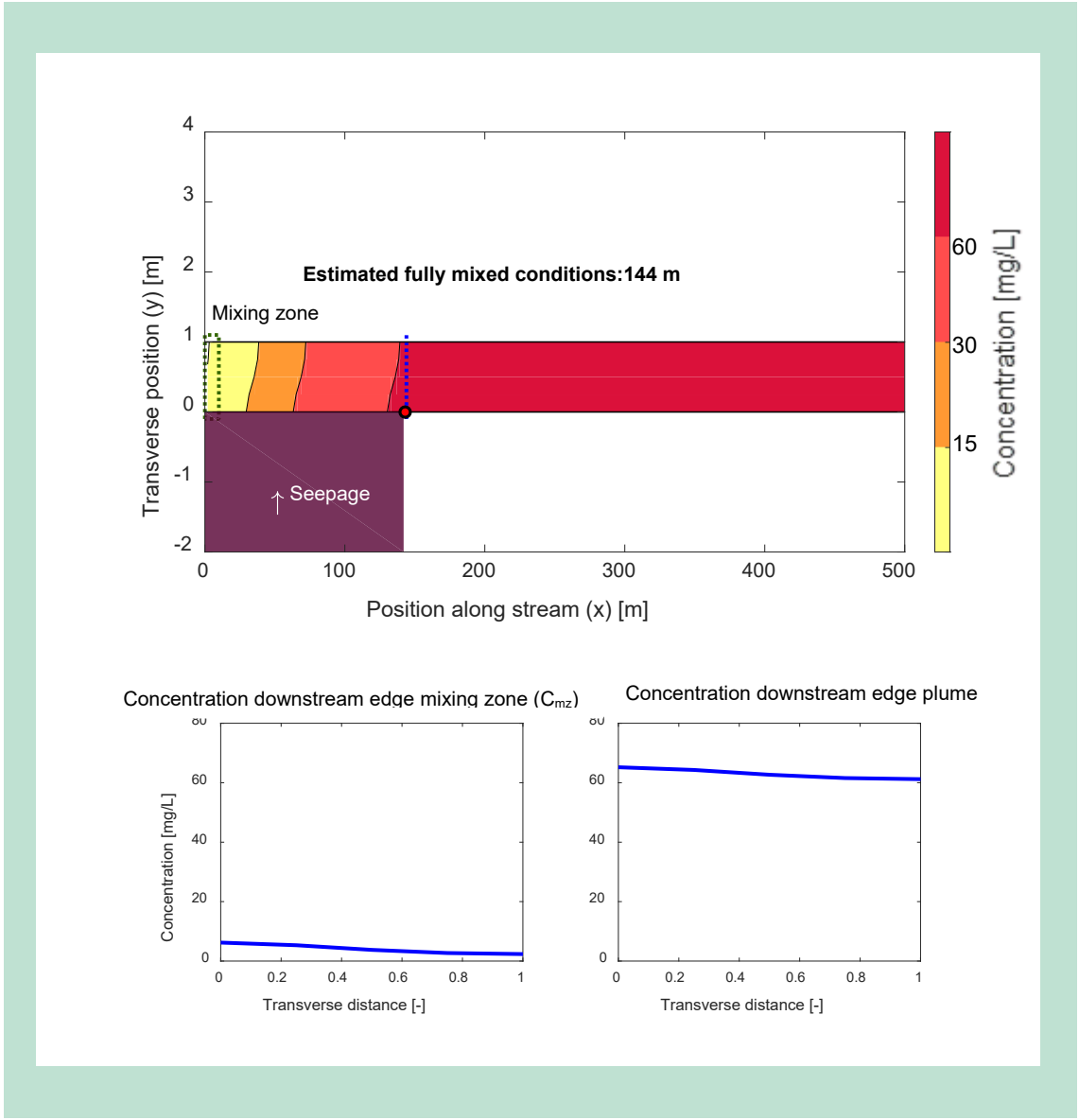


FIGURE 13. Upper graph : Evaluation of the concentration of ammonium-N in stream case 1 (W=1 m, Q = 0.01m3/s) from leachate plume from Tandskov landfill. Plume 142 m wide, with a discharge J = 51599 kg/y uniformly distributed. Dashed blue line: fully mixed conditions defined by eq. (2). Dashed green line: calculated mixing zone. Red marker: maximum concentration.
Lower graphs: concentration at the limit of the calculated mixing zone limit and downstream edge of the plume are presented. Estimated fully mixed concentration: 63.4 µg/L.

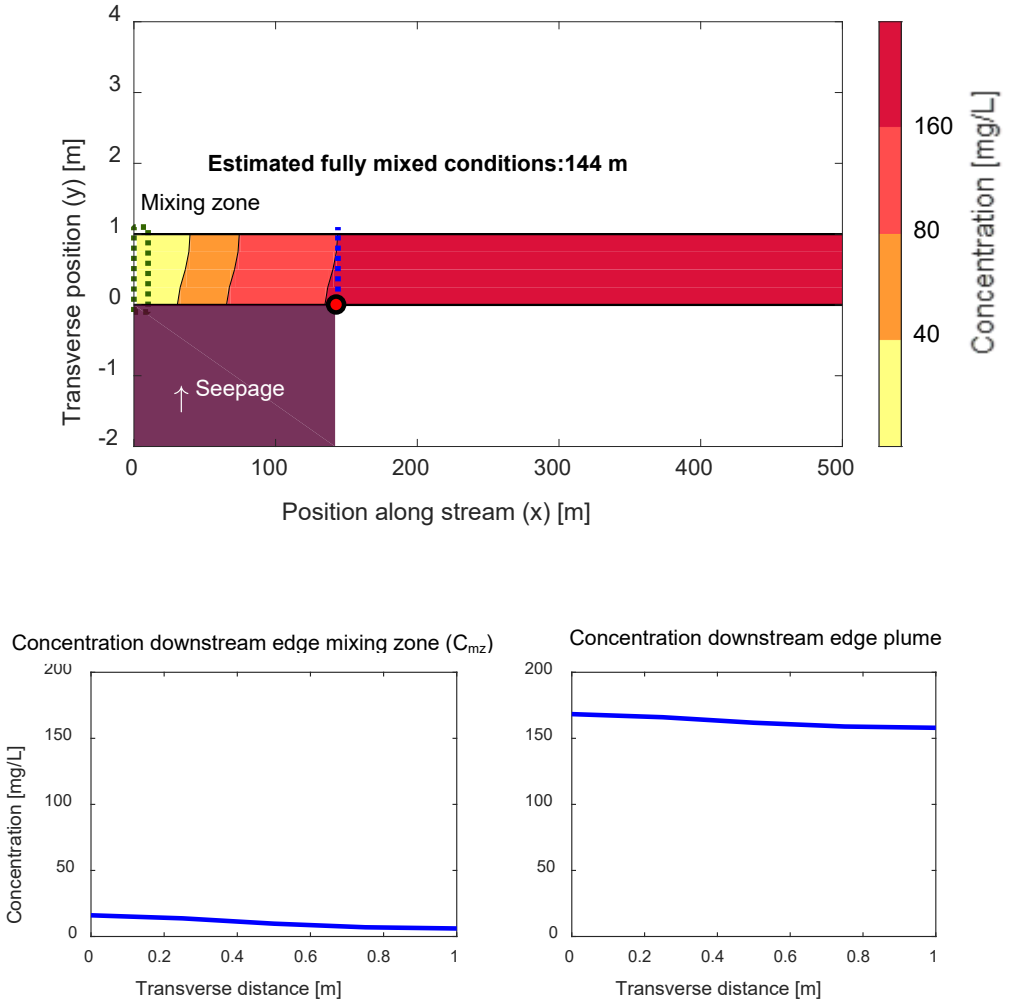


FIGURE 14. Upper graph: Evaluation of the concentration of chloride in stream case 1 (W=1 m, Q = 0.01m3/s) from leachate plume from Tandskov landfill. Plume 142 m wide, with a discharge J = 51599 kg/y uniformly distributed. Blue line: fully mixed conditions defined by eq. (2). Green line: calculated mixing zone. Red marker: maximum concentration.
Lower graphs: concentration at the limit of the calculated mixing zone and downstream edge of the plume are presented. Estimated fully mixed concentration: 163 µg/L.

6.2 Faaborg

Faaborg is an old landfill closed in 1975. This landfill has no leachate collection system nor membrane. It is located close to a wetland and is characterized by complex hydrology conditions (Miljøstyrelsen, 2019). Contaminant mass discharge for the selected leaching compounds are extracted from the output of the transport model simulation (Table 8). For this simulation, only chloride is considered, leaching almost exclusively from part 1 of the landfill (Miljøstyrelsen, 2019). Ammonium is subject to high retardation during the transport phase and does not reach the POC at a distance of 100 m before the limit of 500 years. The estimated concentration at the limit of the calculated mixing zone, maximum concentration and fully mixed concentration in the tested stream cases are given in Table 9.

TABLE 8. Required parameters for assessment of contaminant concentration in streams at Faaborg Landfill. POC = 100 m downstream in the aquifer, all data output from Miljøstyrelsen (2019). All stream parameters defined in Table 2.

Parameters	Value	Comments
Plume width [m]	156	Part 1 only, equal to source width
CMD, ammonium [kg/y]	/	Breakthrough > 500 years
CMD, chloride [kg/y]	10280	Unit 1 only, POC at 100 m downstream

TABLE 9. Estimated concentration in the selected stream cases at the edge of the calculated mixing zone C_{mz}, max. concentration in stream, C_{max} and fully mixed concentrations, C_{mix} for two selected compounds leaching from Faaborg losseplads. Comparison to the requirements defined in Table 1.

Stream case	Chloride [mg/L]			
	EQS	C_{mz}	C_{max}	C_{mix}
1 (W=1 m, Q=0.01 m^3/s)	250	2.9	33.6	32.6
2		/	/	/
3 (W=2 m, Q=0.08 m^3/s)		0.7	4.0	4.3
4		/	/	/
5		/	/	/
6 (W=15 m, Q=8 m3/s)		0.079	0.096	0.040

By using the maximum contaminant mass discharge estimated from the transport model (GrundRisk Landfill) of approximately 10 tons/year, the concentration of chloride complies with the associated requirement even in the worst case of dilution for stream case 1. No exceeding of the requirement is therefore expected in any stream case for the chloride leaching from Faaborg, under the current assumptions.

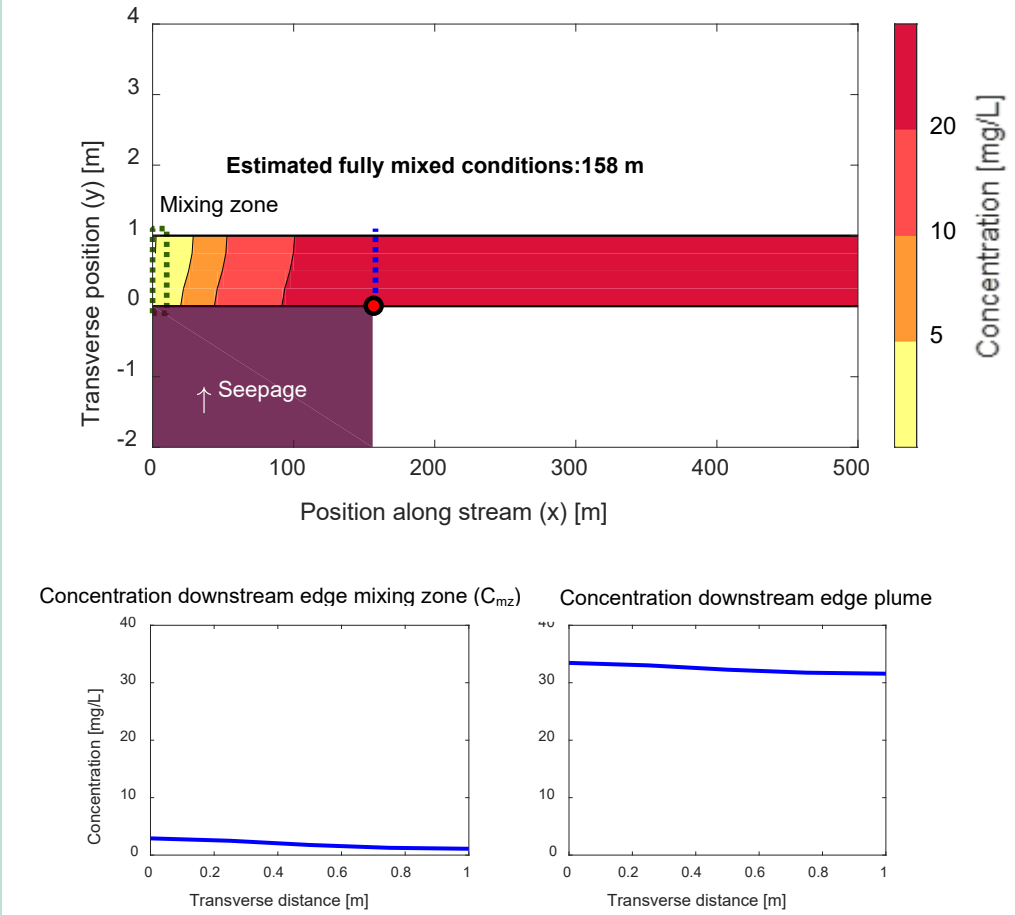


FIGURE 15. Upper graph: Evaluation of the concentration of chloride in stream case 1 (W=1 m, Q = 0.01 m3/s) from leachate plume from Faaborg landfill. Plume 158 m wide, with a discharge J = 20280 kg/y uniformly distributed. Blue line: fully mixed conditions defined by eq. (2). Green line: calculated mixing zone. Red marker: maximum concentration.
Lower graphs: concentration at the limit of the calculated mixing zone and downstream edge of the plume are presented. Estimated fully mixed concentration: 32.6 µg/L.

6.3 Hørløkke

Hørløkke is a former landfill from the seventies used mostly for deposit of construction and demolition waste. Some oil waste was also discovered. This landfill lies right on top of a sandy aquifer approximately 80 m. thick and received a final cover approximately 30 years ago (Miljøstyrelsen, 2019). For this simulation, the fate of three substances is examined: benzene as organic contaminant and two metals nickel and iron. Benzene is degraded during transport in the aquifer. This process is neglected in stream waters due to short retention time (section 4.5.2). The plume of dissolved metals is characterized by non-degradation and retardation factor/sorption processes in the aquifer that “smoothe” the discharge into the aquifer and the stream water consequently. Iron is assumed to be present as ferrous iron (Fe^{2+}) directly discharging into the stream without any change in oxidation state or precipitation processes. The simulation parameters for the potential mixing in stream water are given in Table 10. Results in

terms of concentrations are presented in Table 11 and a visualization of concentration evolution in the stream is presented for the nickel plume, in the stream case 1 (Figure 16).

TABLE 10. Required parameters for assessment of contaminant concentration in streams at Hørløkke Landfill. POC = 100 m downstream in the aquifer, all data output from Miljøstyrelsen (2019). All stream parameters defined in Table 2.

Parameters	Value	Comments
Plume width [m]	116	
CMD nickel [kg/y]	0.18	
CMD iron[kg/y]	185.6	Ferrous iron, no reaction/precipitation
CMD benzene[kg/y]	0.024	Degradation in the aquifer, K = 0.001 day^{-1}

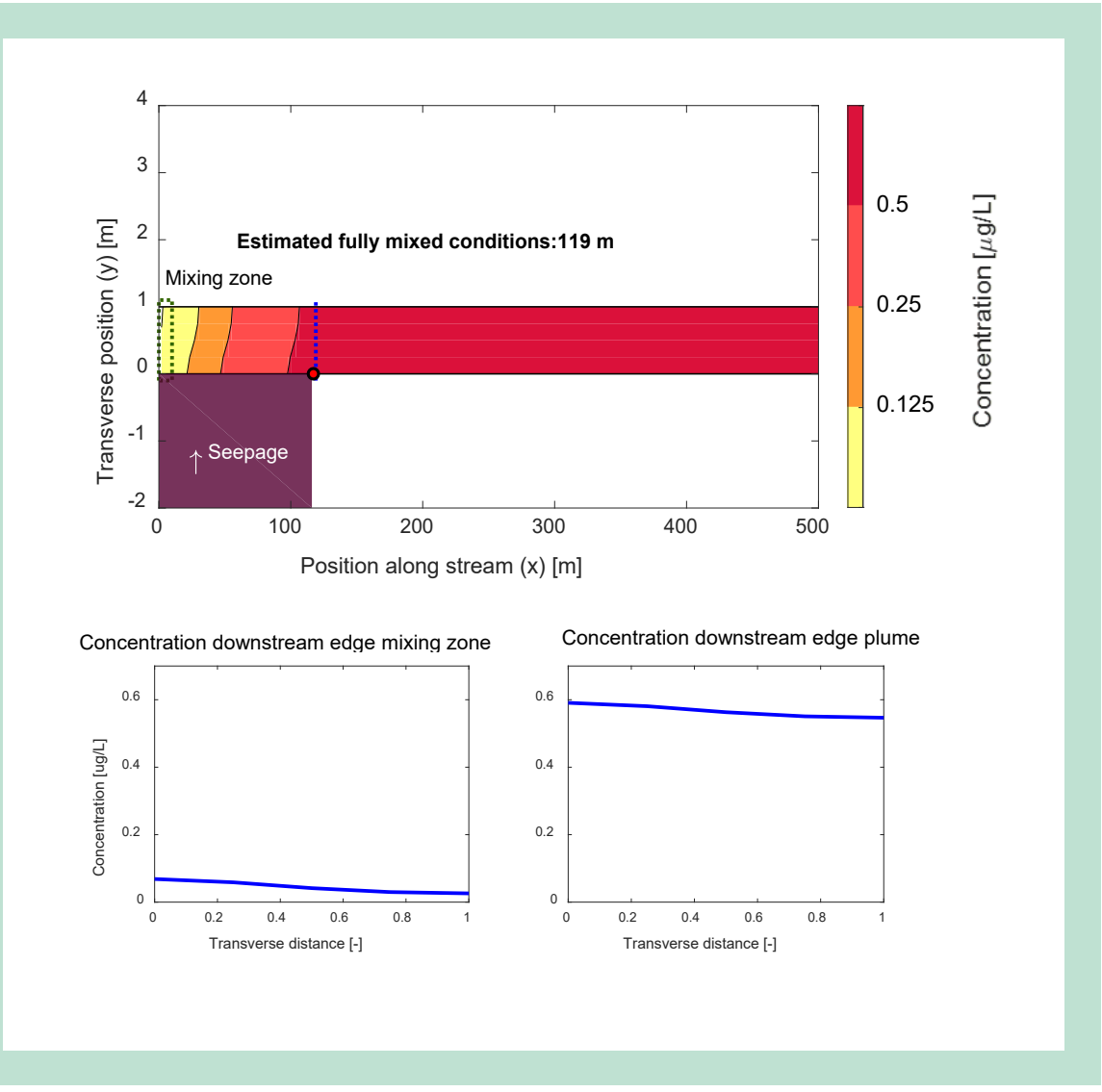


FIGURE 16. Upper graph. Evaluation of the concentration of nickel in stream case 1 (W=1 m, Q = 0.01m3/s) from leachate plume of Hørløkke landfill. The plume is 116 m wide, with a discharge J = 0.18 kg/y uniformly distributed. Dashed blue line: fully mixed conditions defined by eq. (2). Dashed green line: calculated mixing zone. Red marker: maximum concentration. Concentration at the edge of the calculated mixing zone limit and limit of the plume are presented.

Lower graphs: concentration at the limit of the calculated mixing zone and downstream edge of the plume are presented. Estimated fully mixed concentration: 0.05 µg/L.

The estimated concentrations of dissolved nickel in the stream are well below the EQS, with at least one order of magnitude difference even for the most critical case, i.e. small stream. It is expected that the amount of nickel estimated to discharge from Hørløkke landfill does not pose a risk to stream waters. On the other hand, the concentration of dissolved iron could potentially pose a risk for small streams with low dilution factors, as indicated by the concentrations estimated to be 5 times higher than the EQS. For the particular case of iron, it is however important to keep in mind that the discharge in stream water with important amounts of oxygen may lead to oxidation and precipitation with surrounding sediments, not accounted for in the current modelling. Finally, the estimated concentration of benzene in the stream complies with the EQS. The degradation of the organic component during the transport phase in the aquifer is here beneficial and substantially reduces the amount of benzene discharged to the stream.

TABLE 11. Estimated concentration in the selected stream cases at the edge of the calculated mixing zone, C_{mz}, max. concentration in stream C_{max} and fully mixed concentration C_{mix} for two selected metals leaching from Hørløkke losseplads. Comparison to the EQS defined in Table 1.

Stream case	Nickel [µg/L]				Iron [µg/L]			
	EQS	C_{mz}	C_{max}	C_{mix}	EQS	C_{mz}	C_{max}	C_{mix}
1 (W=1 m, Q=0.01 m^3/s)		0.07	0.60	0.57		526	612	587
2		/	/	/				
3 (W=2 m, Q=0.08 m^3/s)	4	0.01	0.08	0.07	100	68	79.4	73.5
4		/	/	/				
5		/	/	/				
6 (W=15 m, Q=8 m^3/s)		0.0007	0.0017	0.0007		0.7	1.7	0.7

TABLE 12. Estimated concentration in the selected stream cases at the edge of the calculated mixing zone C_{mz}, max. concentration in stream C_{max} and fully mixed concentration C_{mix} for benzene leaching from Hørløkke losseplads. Comparison to the EQS defined in Table 1.

Stream case	Concentration benzene [µg/L]			
	EQS	C_{mz}	C_{max}	C_{mix}
1 (W=1 m, Q=0.01 m3/s)	10	0.07	0.07	0.05
2		/	/	/
3 (W=2 m, Q=0.08 m3/s)		0.009	0.010	0.009
4		/	/	/
5		/	/	/
6 (W=15 m, Q=8 m3/s)		9.4e-5	22e-5	9.4e-5

7. Discussion, conclusions and recommendations

7.1 Objectives of the project

This report is the result of a general investigation of the environmental impact of landfills. The current report focuses on the potential impact of landfills on surface waters, and more specifically the processes in play when a leachate plume originating from a landfill reaches and dilutes in streams. An analytical model for the evaluation of the contaminant mixing and dilution in streams is presented and a general methodology is proposed for the evaluation of the resulting contaminant concentrations. As examples of the applicability of the model the expected dilution is estimated for selected contaminants in streams from the leaching of three landfills used as example for this project: Tandskov, Faaborg and Hørløkke in Denmark.

7.2 Limitations and assumptions

All observations and given conclusions are based on the assumptions inherent to the model and the calculation. A summary of these assumptions is given below.

TABLE 13. Main limitations and assumptions for the assessment of the mixing of leachate plumes in streams.

Parameters	Comments
Stream geometry	Rectangular cross section, straight stream
Contaminant properties	Geochemical processes: degradation, volatilization, precipitation/dissolution not considered
Contaminant distribution	Uniform distribution, based on the assumption of the source term and transport models and only one landfill cell at a time
Water balance	The groundwater seeping into the investigated streach is not accounted for and considered negligible in comparison to the stream flow.

For the mixing distances, the simplified assumptions about the stream (rectangular cross section and straight stream) results in mixing distances likely longer than in reality. In a realistic scenario, the natural obstacles, pooling and sliding combined to slight meanders will reduce this distance. No analytical formulations are currently available to assess the effect of these features but it is believed that the conclusion given previously will not change drastically, i.e. the calculated mixing zones as defined by the Danish Environmental Protection Agency do not fit the size of landfill leachate plumes.

For a number of substances, degradation, volatilization and other processes, such as precipitation as already mentioned for iron, will result in lower concentrations than the ones estimated by the model. The importance of the hyporheic zone at the interface of groundwater and stream water in terms of contaminant degradation and sorption is also omitted.

The mixing dilution model does not account for the water discharged by groundwater with the contamination. This assumption can be challenged with leachate plumes several hundred meters large constituting a large seepage front compared to small streams with low flow rate for

example. The dilution can therefore be more important than anticipated. Nevertheless, this assumption can be judged as a relevant conservative approach in the case of a risk assessment.

For many landfills, the division in different cells will lead to complex contaminant distribution that was not discussed in the current report. These arrangements will modify the contaminant distribution when transported in the aquifer and further away when discharged into the stream. The influence on the mixing distance cannot be estimated by the current model and is strongly dependent on the combination of the distribution of contaminant discharge from each individual cells (location, waste composition, concentrations etc.) and use of non-uniform distribution in an updated model is required. With respect to the resulting concentration for a given compound, a summation of the contribution from each individual source is relevant.

7.3 Overview of results and conclusions

The mixing and dilution of contaminant in streams was investigated for six representative stream cases with a dedicated mixing/dilution model, ranging from small streams with low flow to large streams with high flows. The simulations and consequent observations were compared to a Monte Carlo simulation for generalization and lead to similar conclusions: In the case of landfill leachate plumes, both mixing zones and calculated mixing zones are smaller than the width of most leachate plumes and thus, the width of the leachate plume as well as the site of maximum contaminant concentration are not contained within the mixing zone/calculated mixing zone.

The calculation results show that the mixing length, i.e. the point where concentration is fully mixed is almost every time found downstream of the mixing zone (with dimensions defined by the Danish Environmental Protection Agency (Miljøstyrelsen, n.d.)) and the calculated mixing zone (as defined by the Danish Environmental Protection Agency for use in the initial screening of contaminated sites carried out by the Danish Regions (Miljøstyrelsen, n.d.b)). This mixing length is dependent both on the stream geometry, flow rate, but is also influenced by the location of the plume discharge into the stream as well as its dimension for a given contaminant mass discharge. The generalized approach by Monte Carlo Simulation indicates mixing length in the order of 36 to 62 times the width of the plume from the upstream edge of the plume, much higher than the 10 times stream width used in Danish legislation (section 5.2). This size difference has two major implications: First, the contaminant concentration at the limit of the calculated mixing zone may not be fully mixed. This implies that the concentration in the corresponding stream section is not constant, making the use of a single Point Of Compliance (POC) dependent on the transverse coordinate in the stream that needs to be clearly stated. Secondly, the concentration at the limit of the calculated mixing zone can be found lower than the maximum concentration and fully mixed concentration observed in stream at the downstream edge of the plume where all contaminant mass has been discharged, especially for small streams (Figure 8, 11).

Thus, it can be concluded that the concentrations at the limit of the calculated mixing zone are not entirely fully mixed and can underestimate the fully mixed and maximum concentration found downstream of the plume from uncontrolled landfills, especially for small streams. It is also not certain which concentrations (maximum, fully mixed) should be compared to the EQS.

Some simulations were carried out for three examples of landfills and selected compounds. The case of small streams appears to be the most problematic for several of the compounds (e.g. iron in Hørløkke, nitrogen in Tandskov) due to the low dilution achieved in the streams. This will most likely be the case for other compounds also, depending on their presence in the landfill leachate and chemical properties.

The assessment carried out for the three landfills raised the issue of the relevance of the requirements for some of the substances present in the landfill leachate and not covered yet in the relevant legal document (Miljøministeriet, 2017). For this study, the drinking water criteria were used for chloride, ammonium and ferrous iron. These criteria are developed for humans and not for freshwater ecosystems and relevant EQS should therefore be made in case of risk assessment. Additionally, it could also be discussed if the ammonium discharge instead should be compared to general requirement of total load in stream surfaces such as “udledningsskrav” for agriculture and fish farms.

7.4 Strategy for Point of Compliance and mixing zone definition

To properly evaluate the risk associated with the contamination from a leachate plume, it is mandatory that the defined Point of Compliance lies beyond the downstream edge of the plume where all contaminant mass for the investigated plume has seeped into the stream and starts mixing. Consequently, a definition of the mixing zone and calculated mixing zone for leachate plumes at the downstream edge of the plume is suggested. The concentration should be fully mixed at the downstream limit of this zone, and therefore, this fully mixed concentration should be the quantity to monitor/estimate. With respect to estimation, the fully mixed concentration is an output of the present model. In the case of measurement, a sampling at the point where fully mixed conditions are achieved is simple as theoretically only one point in a stream transect would be necessary, independent of the transverse location (at the point of fully mixed condition, the concentration is almost constant within a section). This nevertheless requires knowledge about where the fully mixed conditions are achieved.

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Appendix 2. Input parameters for the mixing/dilution model in streams

Parameters		Comment
Stream		
	Width [m]	
	Depth [m]	
	Slope [-]	
	Flow rate [m^3/s]	
Contaminant		
	Plume coordinate [m]	Location of the upstream point of the plume ()
	Plume width [m]	
	Mass discharge [kg/y]	
	C background	If background concentration already present
	Seepage location	From bank / half a streambed
Other parameters		
	Mixing coefficient [m^2/s]	Turbulent mixing coefficient. Transverse $\xi_{o,t}$: 0.3 Vertical $\xi_{o,v}$: 0.067

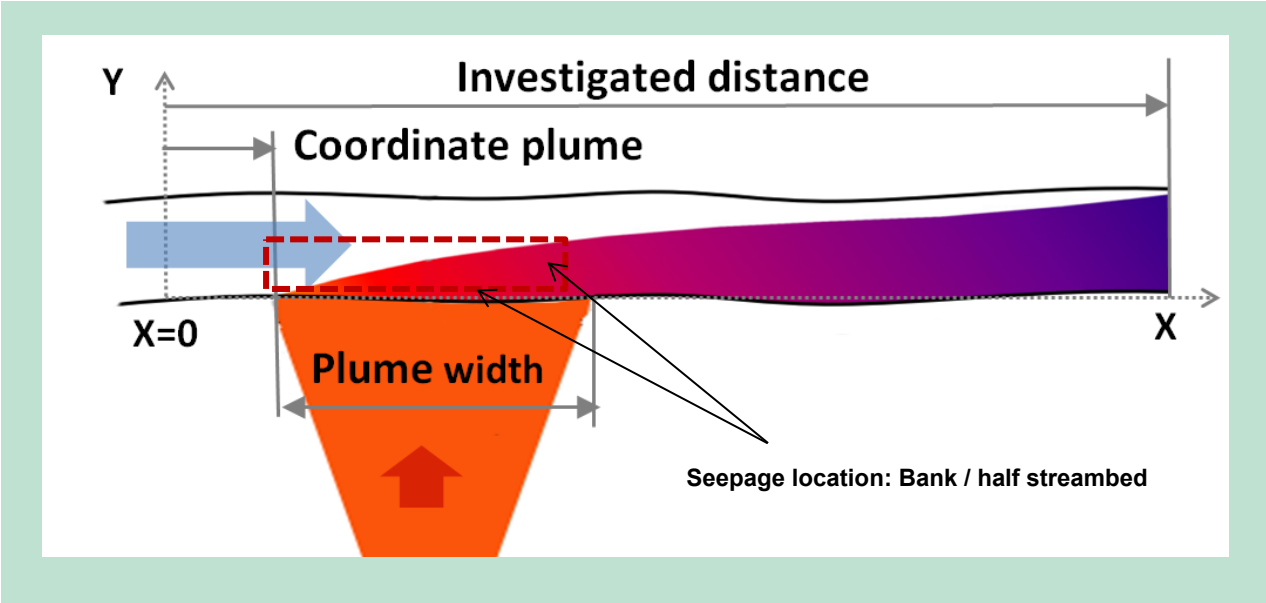

FIGURE 177. Schematic visualization of the required parameters for the mixing/dilution model.

Appendix 3. Effect of plume width and spreading on the mixing length in the stream

Appendix 3.1 Transport model parameters

TABLE 14. Test case for the effect of the plume width and distribution with respect to mixing in surface water Parameter for the transport model from Tandskov landfill case (Locatteli et al. 2017).

Parameter	Value	Remark
Source length [m] (flow direction)	320	
Source width [m]	170	
GW pore velocity [m/y]	70	
Source concentration [µg/L]	20	
Infiltration source area [mm/y]	500	
Infiltration over plume [mm/y]	-	
Porosity [-]	0.3	
Bulk density aquifer [g/cm3]	1.86	
Source concentration [ug/L]	20	For example only
Degradation rate [1/T]	0	No degradation
Dispersivity $\alpha_L - \alpha_T - \alpha_V$ [m]	1 – 0.01 -0.005	
Model type	2D model	Assume all contaminant enters the streams

Appendix 3.2 Stream model parameters

All stream parameters are given in Table 2 completed with the general parameters below in Table 15.

TABLE 15. General model parameters for the mixing of contaminant in streams

Parameter	Value	Remark
Transverse mixing constant $\xi_{o,t}$[m^2/s]	0.3	See (Miljøstyrelsen, 2014d) for details
Vertical mixing constant $\xi_{o,l}$[m^2/s]	0.067	See (Miljøstyrelsen, 2014d) for details
Volatilization rate [1/T]	0	No degradation

Appendix 3.3 Effect of plume dispersion with respect to contaminant mixing and concentrations (plume 20 m large)

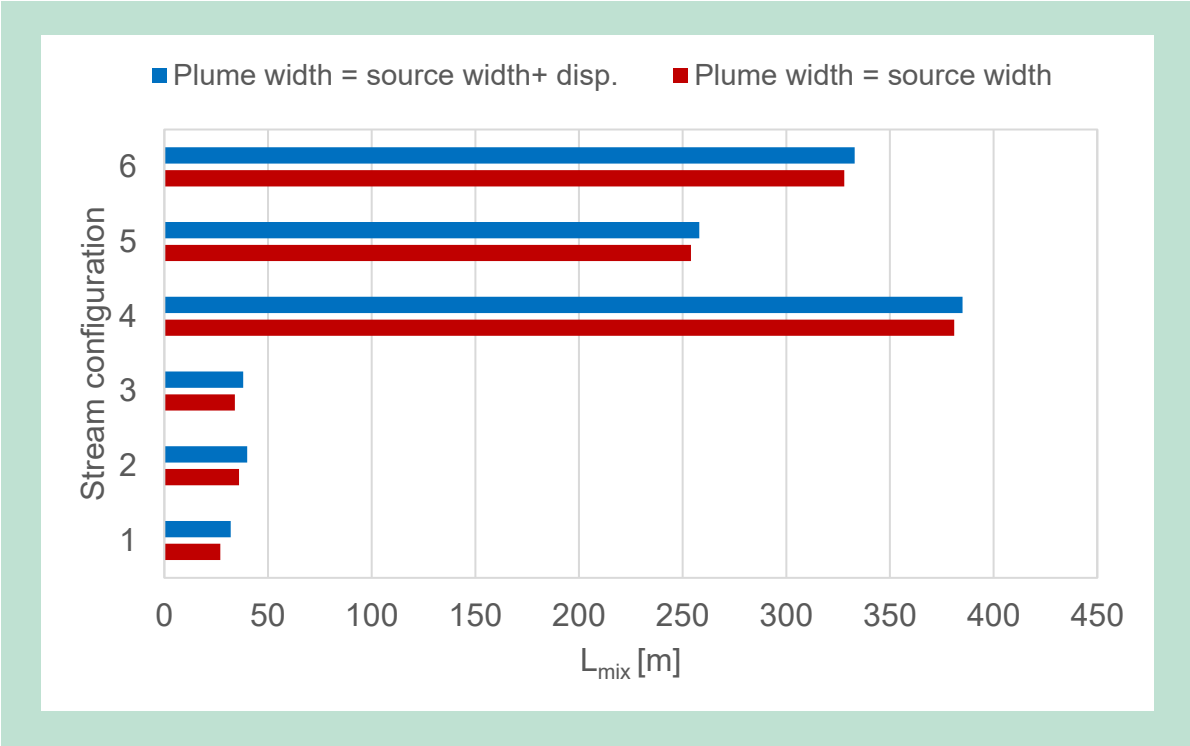

FIGURE 18. Effect of plume width and dispersion in the aquifer on the mixing length. Plume width = 20 m, 1 kg/y from bank.

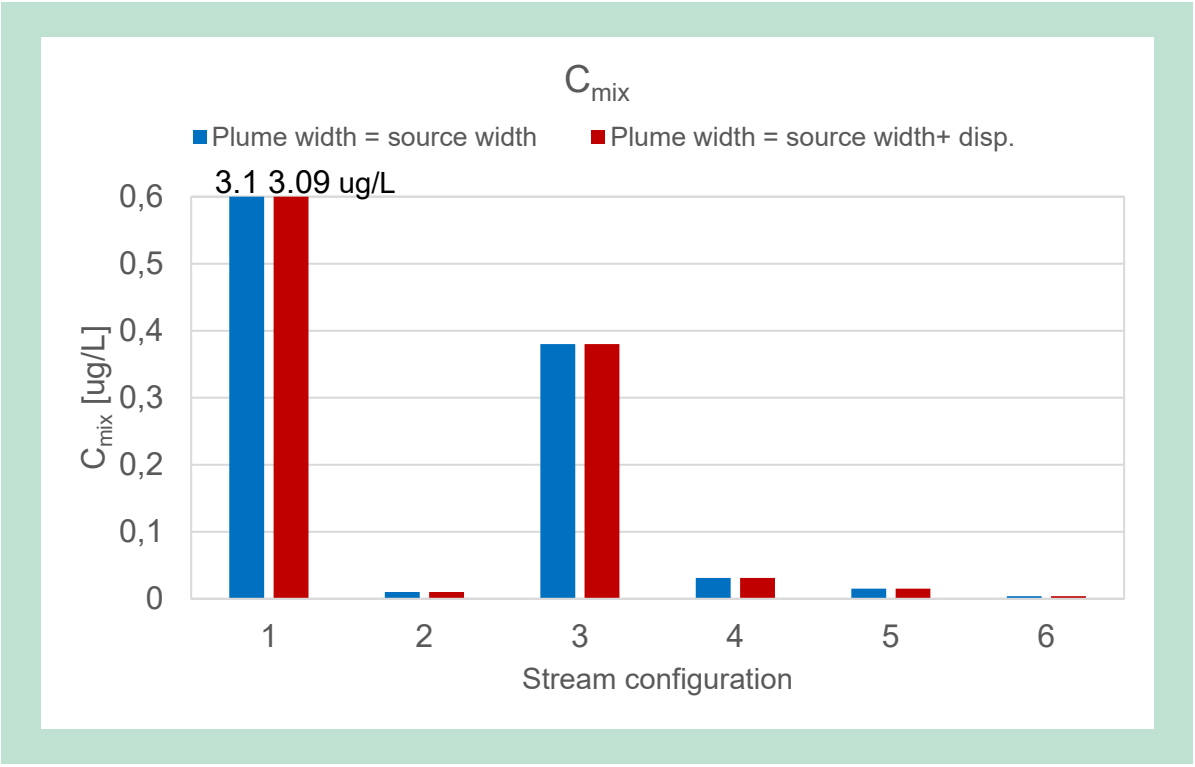

FIGURE 19. Effect of plume width and dispersion in the aquifer on the fully mixed concentration. Plume width = 20 m, 1 kg/y from bank.

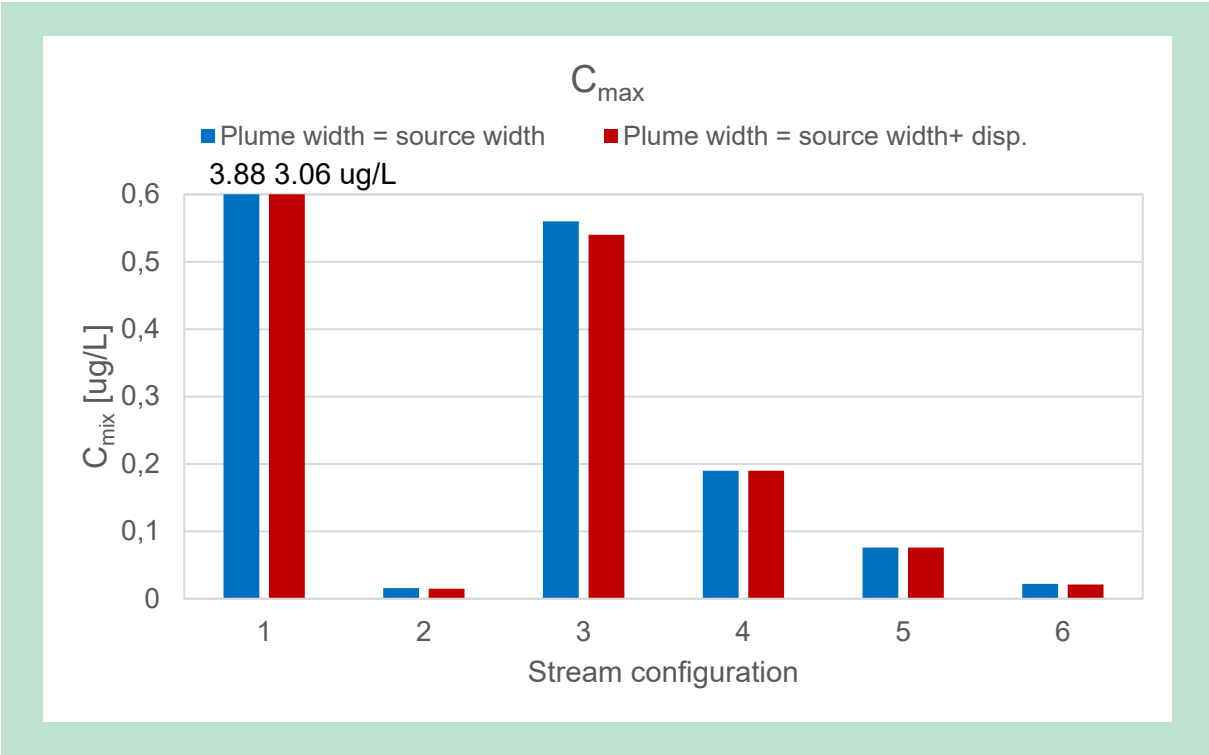

FIGURE 20. Effect of plume width and dispersion in the aquifer on the maximum concentration. Plume width = 20 m, 1 kg/y from bank.

Appendix 3.4 Effect of plume dispersion with respect to contaminant mixing and concentrations (plume 170 m large)

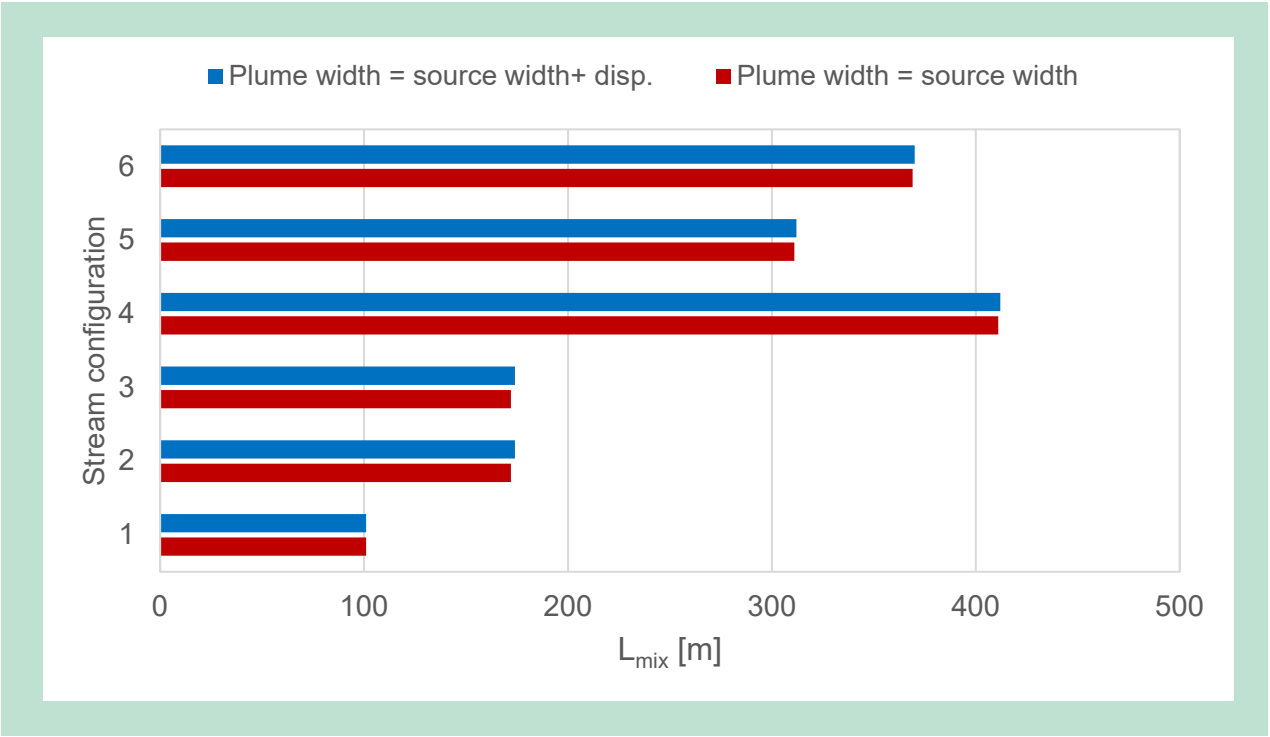

FIGURE 21. Effect of plume width and dispersion in the aquifer on the mixing length. Plume width = 170 m, 1 kg/y from bank.

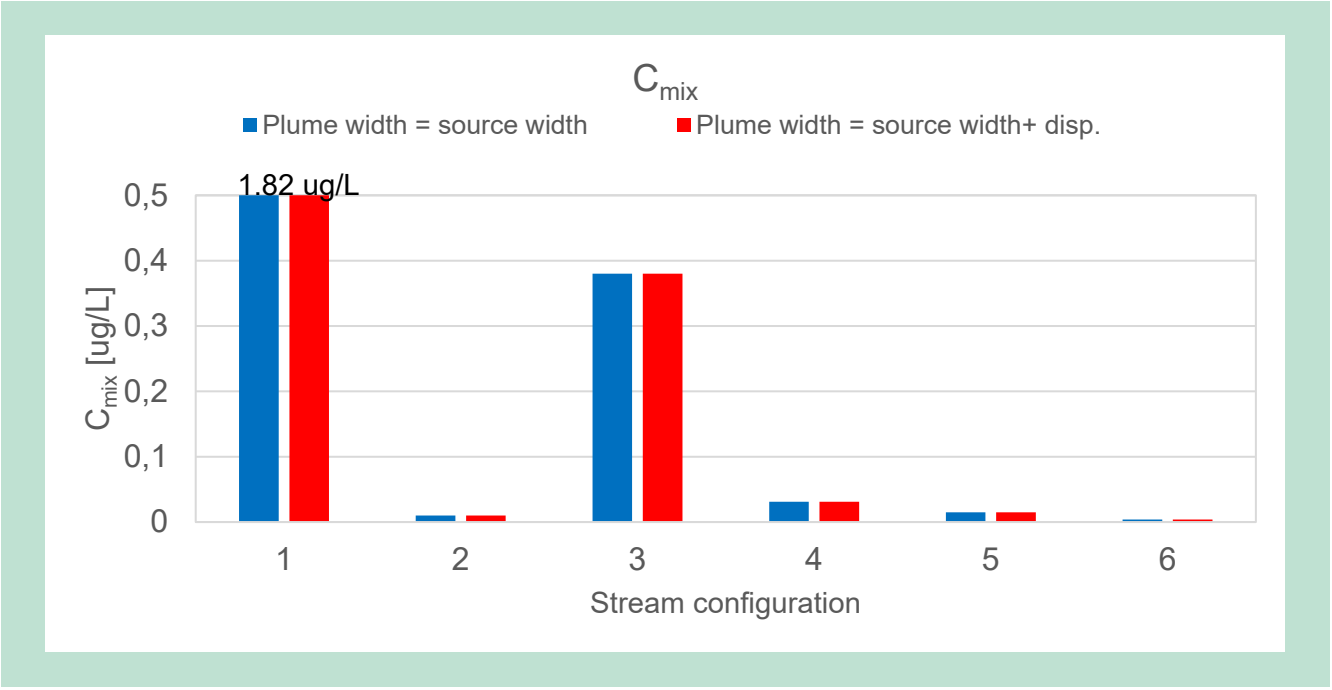

FIGURE 22. Effect of plume width and dispersion in the aquifer on the fully mixed concentration. Plume width = 170 m, 1 kg/y from bank.

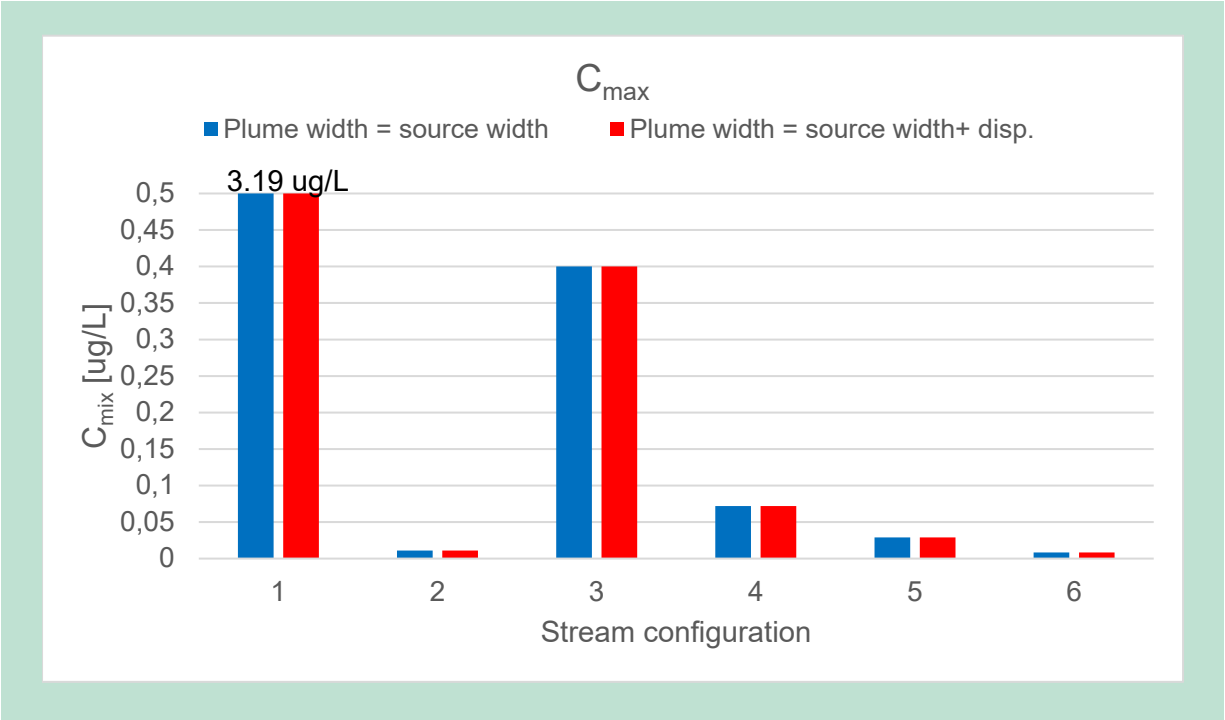

FIGURE 23. Effect of plume width and dispersion in the aquifer on the maximum concentration. Plume width = 170 m, 1 kg/y from bank.

Appendix 4. Contour maps of contaminant mixing in stream (normalized leachate plume, 1 kg/y)

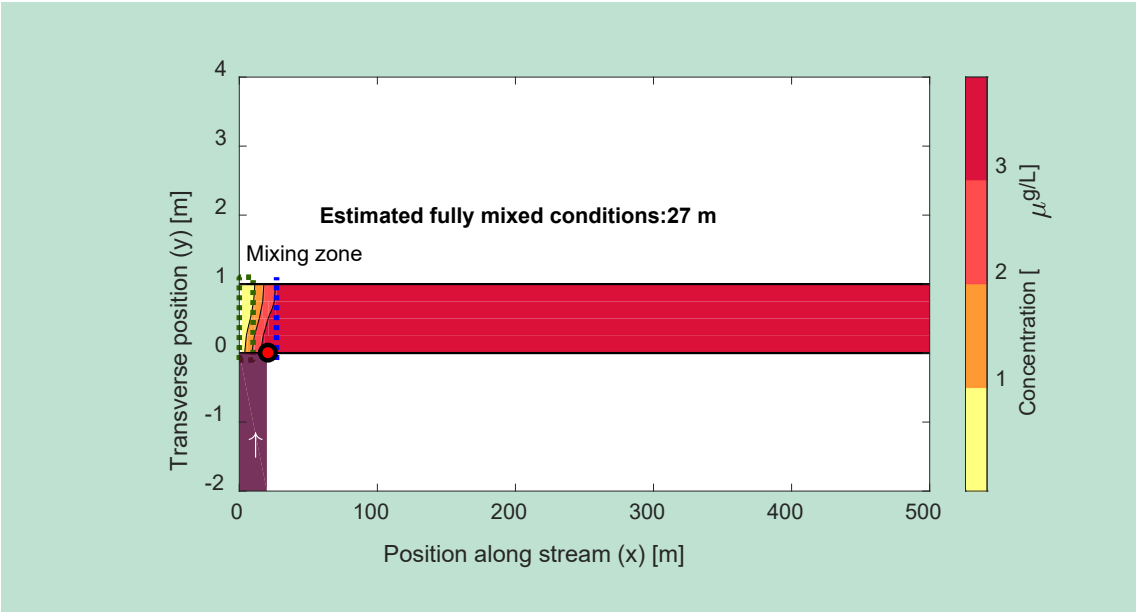

FIGURE 24. Small stream case 1 (low flow), plume 20 m wide.

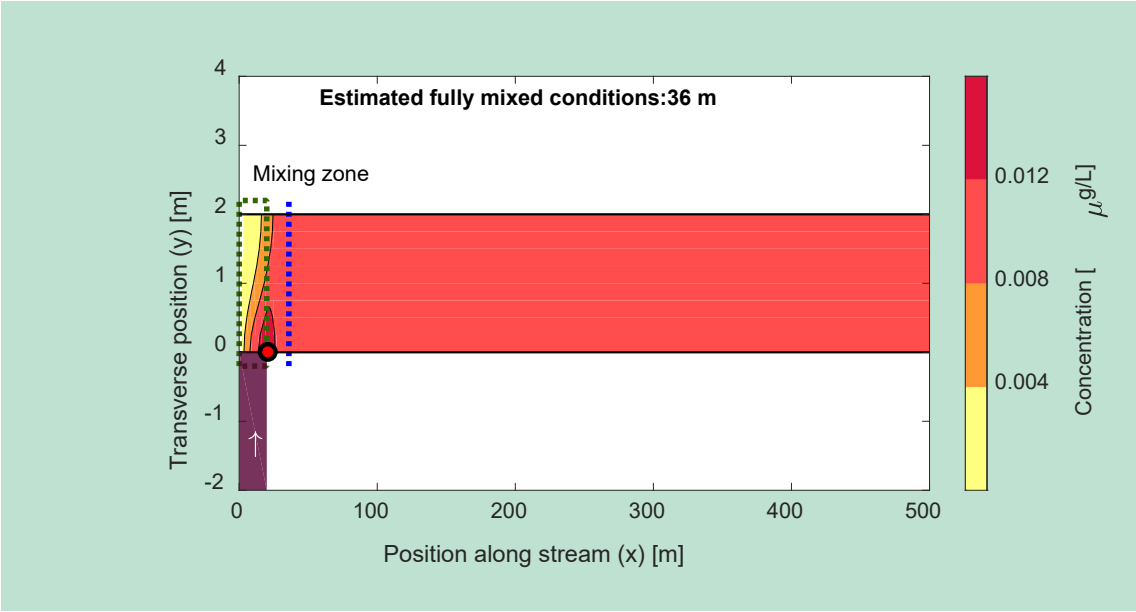

FIGURE 25. Small stream case 2 (low flow), plume 20 m wide.

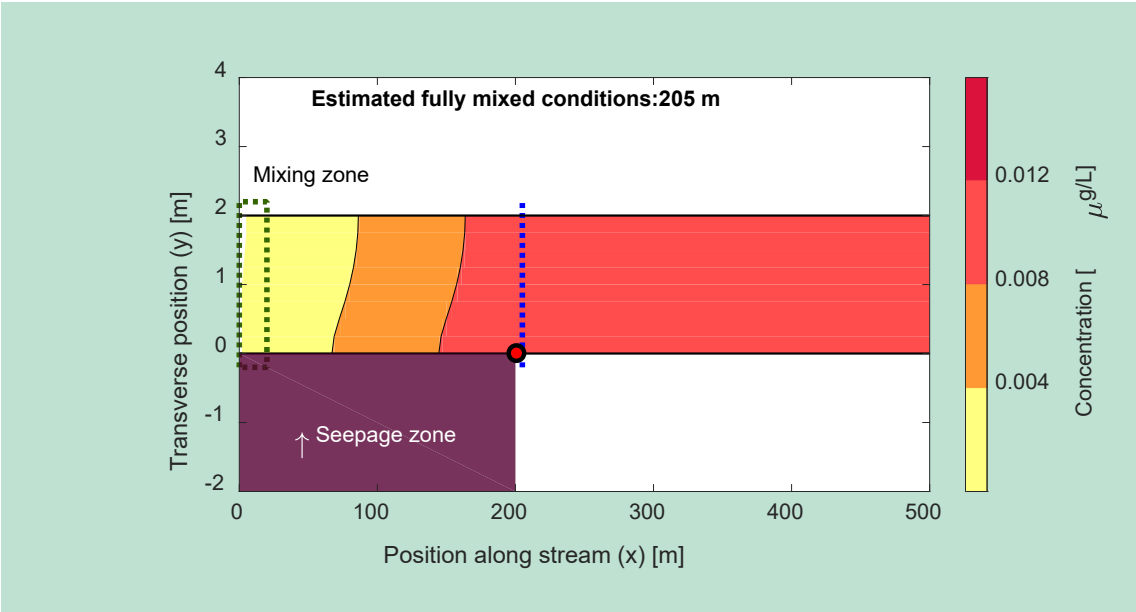

FIGURE 26. Small stream case 2 (high flow), plume 200 m wide.

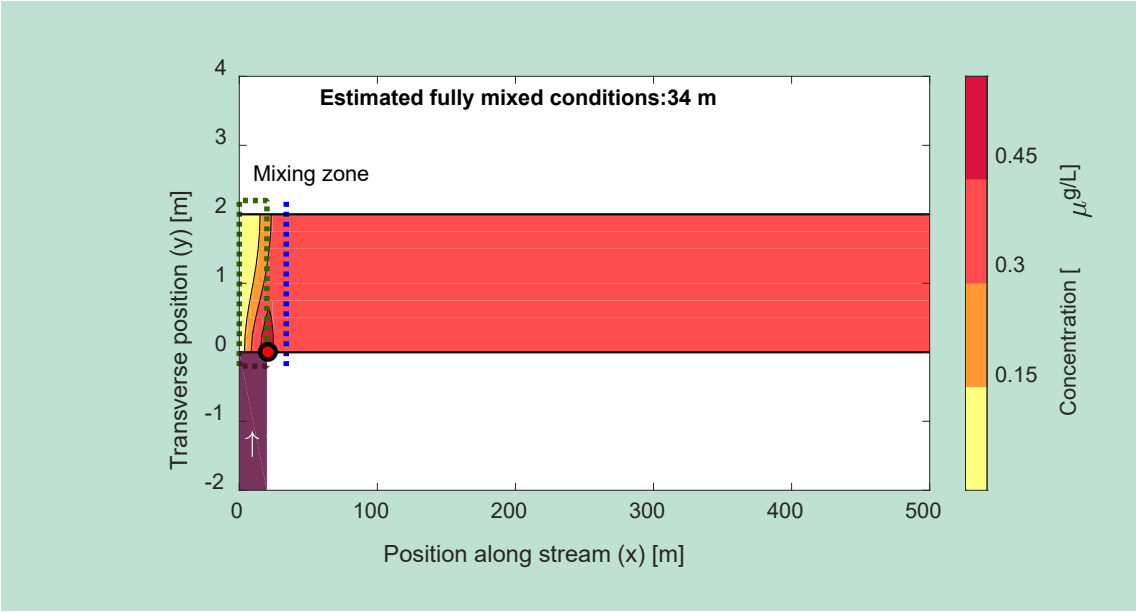

FIGURE 27. Medium stream case 3 (low flow), plume 20 m wide.

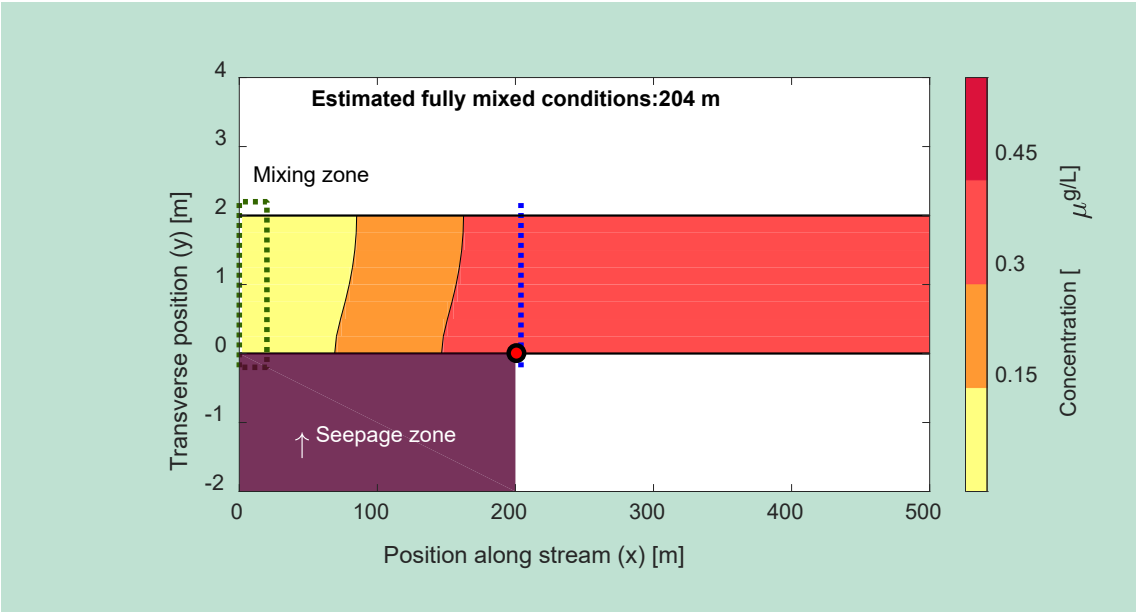

FIGURE 28. Medium stream case 3 (low flow), plume 200 m wide.

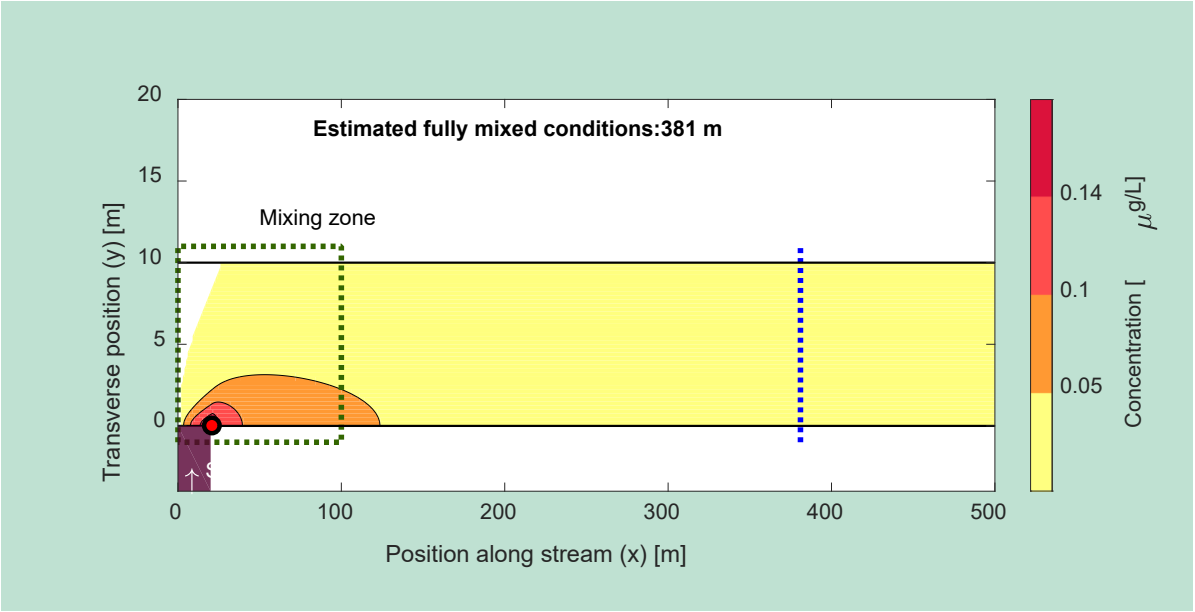

FIGURE 29. Medium stream case 4 (high flow), plume 20 m wide.

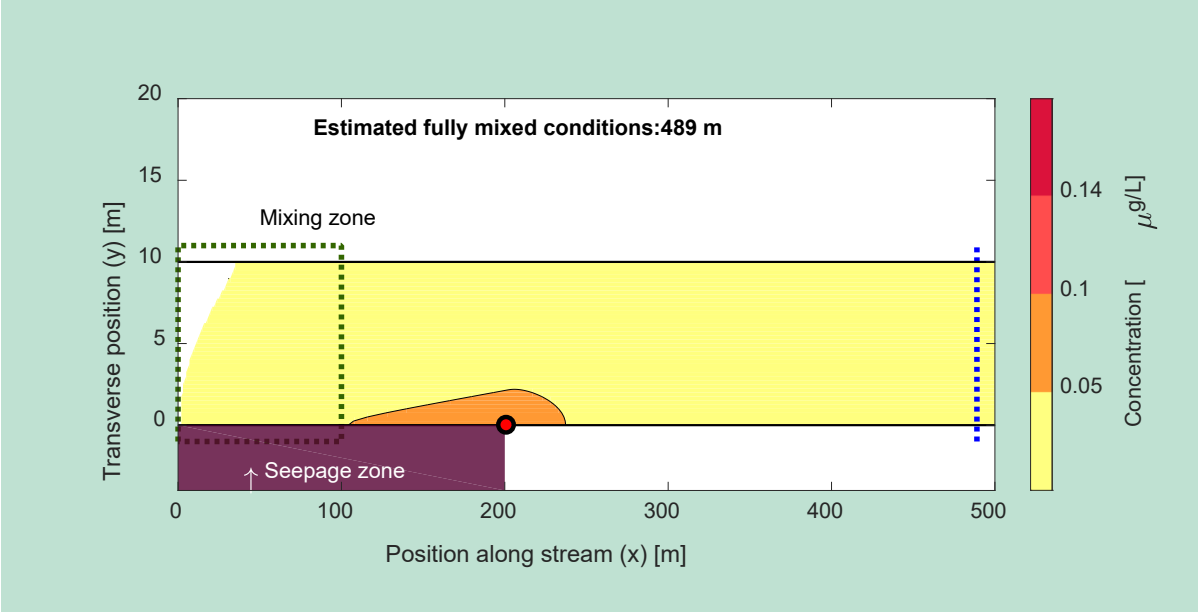

FIGURE 30. Medium stream case 4 (high flow), plume 200 m wide.

Appendix 5. Example of fully mixed conditions achieved within the plume width stretch

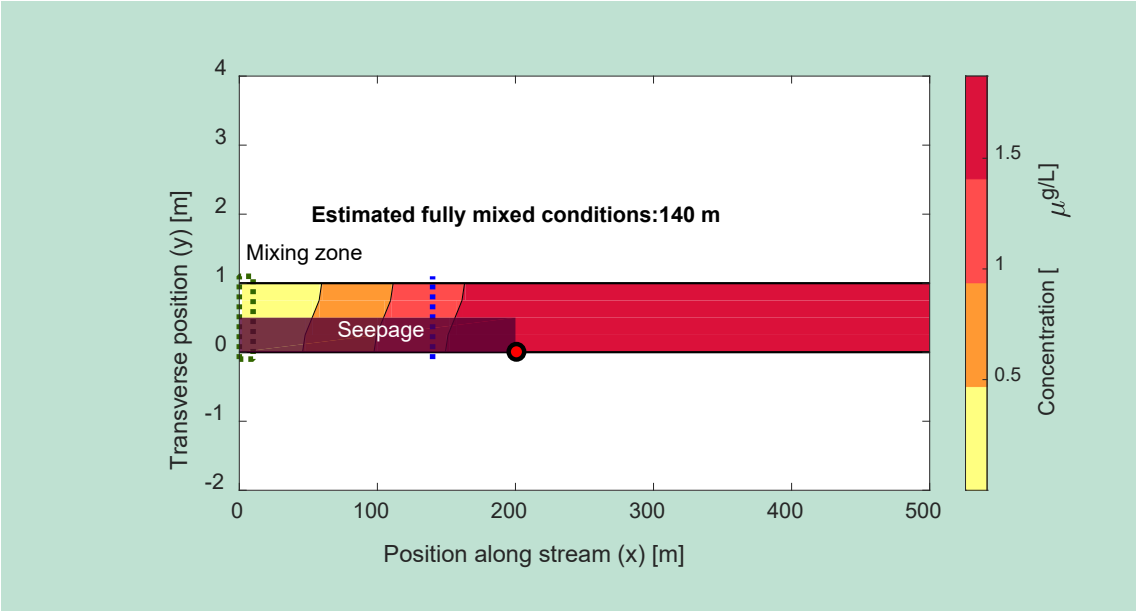

FIGURE 31. Evolution of the contaminant concentration in stream case 1 (W=1 m, Q = 0.01 m3/s), top view. Plume 200 m wide, with a discharge J = 1kg/y, uniformly distributed, discharging from streambed. Dashed blue line: fully mixed conditions defined by eq. (2). Dashed green line: Calculated mixing zone. Red marker: maximum concentration.

Assuming a discharge from the streambed and a stream case 1, the fully mixed conditions are achieved prior to the downstream edge of the plume. The contaminant entering the stream between the fully mixed condition and the downstream edge of the plume do not significantly impact the already achieved fully mixed conditions.

Appendix 6. Estimated/measured concentration of target substances at the three selected landfills (from Miljøstyrelsen, 2019)

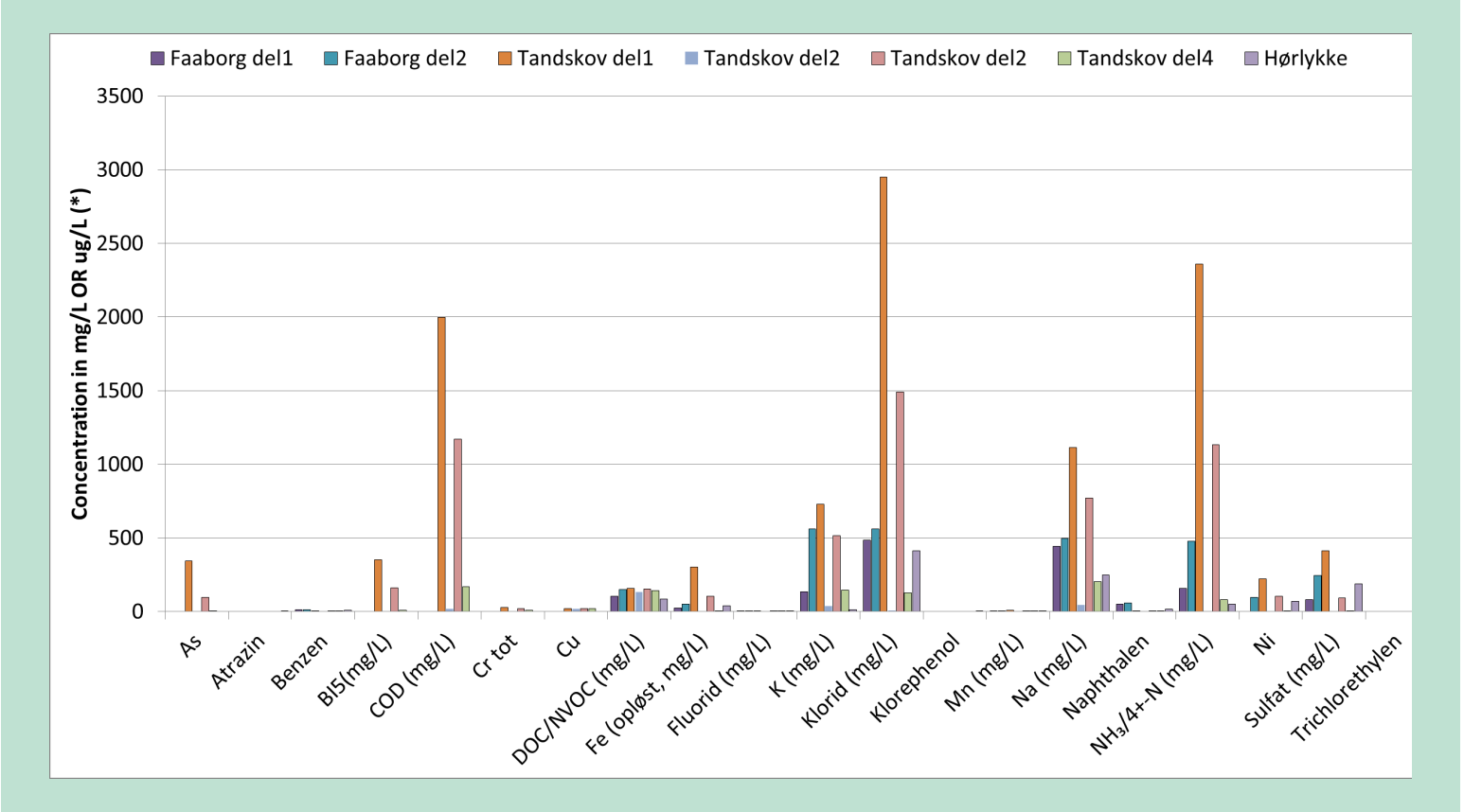

FIGURE 32.

Appendix 7. Evaluation of fully mixed condition point and associated concentration (normalized leachate plume 20 m – 1 kg/y)

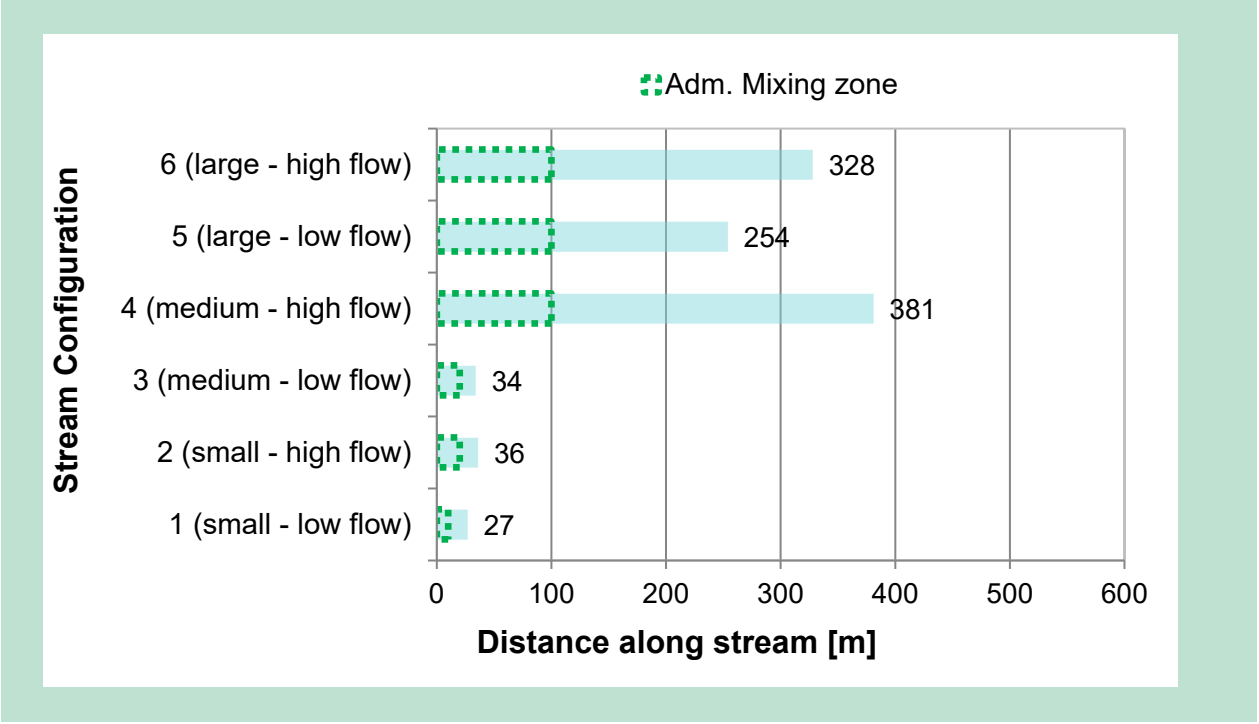

FIGURE 33. Evaluation of fully mixed conditions for the different stream cases and comparison to the calculated (administrative) mixing zone. Leachate plume : 20 m wide.

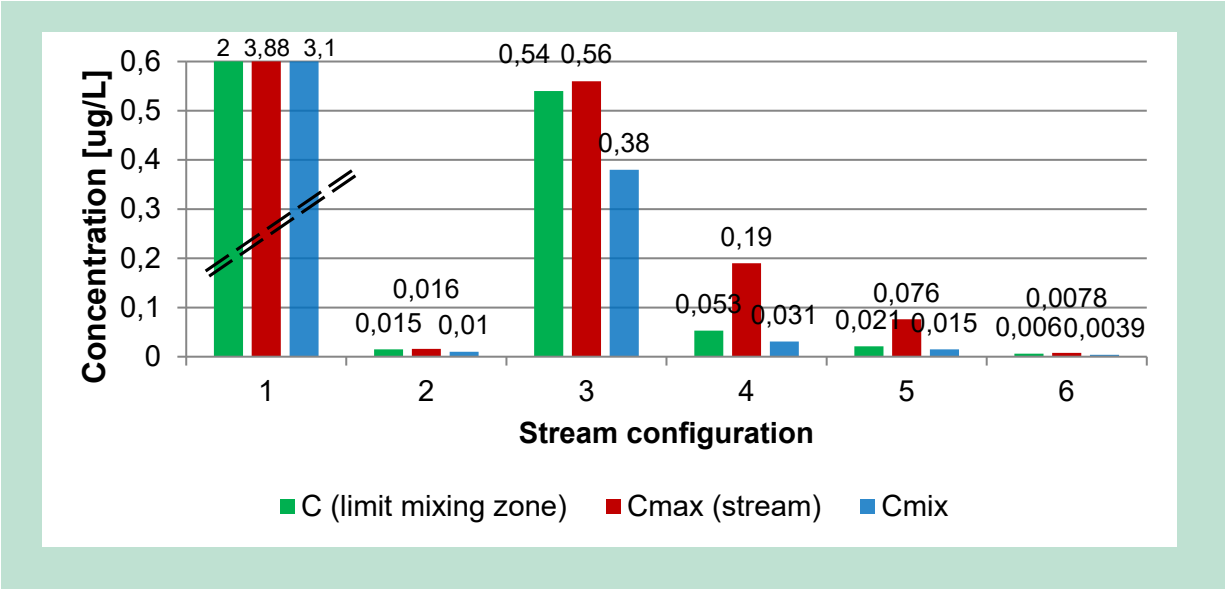

FIGURE 34. Comparison of maximum concentration at the limit of the calculated mixing zone C_{mz}, maximum concentration in the stream C_{max} and fully mixed concentration C_{mix}. Plume width 20 m (The dashed line shows a break in the y-axis to facilitate the reading of low and high values).

Appendix 8. Definition and estimation of the stream case parameters

The different investigated stream cases were defined using the following approach:

- Width selection: based on the minimum and maximum width as defined by Miljøstyrelsen (2014d)
- Flow rate: the 10% and 90% quantile of flow rate distribution (Miljøstyrelsen, 2015) were used as minimum and maximum flow associated to minimum and maximum width respectively.
- Slope: in the absence of relevant data, a default slope of 0.0005 is chosen, as previously used for the investigation of pollutant discharge from contaminated sites (Miljøstyrelsen, 2014d)
- Depth: the depth is calculated using the relationship between all the previous parameters and use of Manning's equation assuming a rectangular cross section:

$$Q = \frac{A}{n} {R_h}^{2/3} \sqrt{S} \qquad \text{Eq. (3)}$$

With Q flow rate, A area of the cross section, n Manning's coefficient, R_h hydraulic radius, and S slope. A coefficient n=0.14 is selected corresponding to "channels not maintained, weeds and brush uncut". A high value of n is deliberately chosen here to account for the fact that most streams are actually not rectangular and smooth channel but rough and non-regular. Three validation cases from measurements were used to validate the relevance of the approach (Table 16). The flow rate is either over- or under-estimated compared to the measured data but the deviation is deemed acceptable considering the extreme simplification of the stream cross section to a rectangular shape.

TABLE 146. Validation of depth/Flow rate by Manning's Formula Validation on measurement cases performed by DTU.

Validation case	Measured Q [m^3/s]	Estimated Q [m^3/s, n = 0.14] Deviation from measurement	Comment
Large stream W=10m, d=1.75m, S=0.1‰	2.13	1.48 (-30%)	
Medium stream W= 10 m, d= 0.8 m, S = 0.1‰	0.32	0.51 (+60%)	
Small stream (depth) W=7, d=0.3 m, S = 0.1‰	0.050	0.063 (+26%)	

Appendix 9. Generalization of results to all stream configurations

In this appendix, a result of a Monte Carlo simulation is presented to asses the values defined for each stream category,with a random stream width, a random flow rate and a random slope between. Depth is calculated backwards using Manning's Equation as explained in Appendix 8. If existing, all configurations with depth > width are ruled out, as they are considered not realistic. 1000 configurations are kept as the default dataset. The results are presented below, arranged after stream category.

Appendix 9.1 Small streams

The parameter bounds for the MC simulation of small stream configurations are given in Table 17. The results in terms of fully mixed concentration, maximum concentration and concentration at the limit of the calculated mixing zone are presented in Figure 35.

TABLE 157. Upper and lower bound of the different simulation variables Small stream category.

Parameter	Variation range
W [m]	[1-2]
Q [m3/s]	[0.01-3]
S	[0.0005-0.01]
Plume width [m]	[5-500]
Mass discharge [kg/y]	[100-50000]

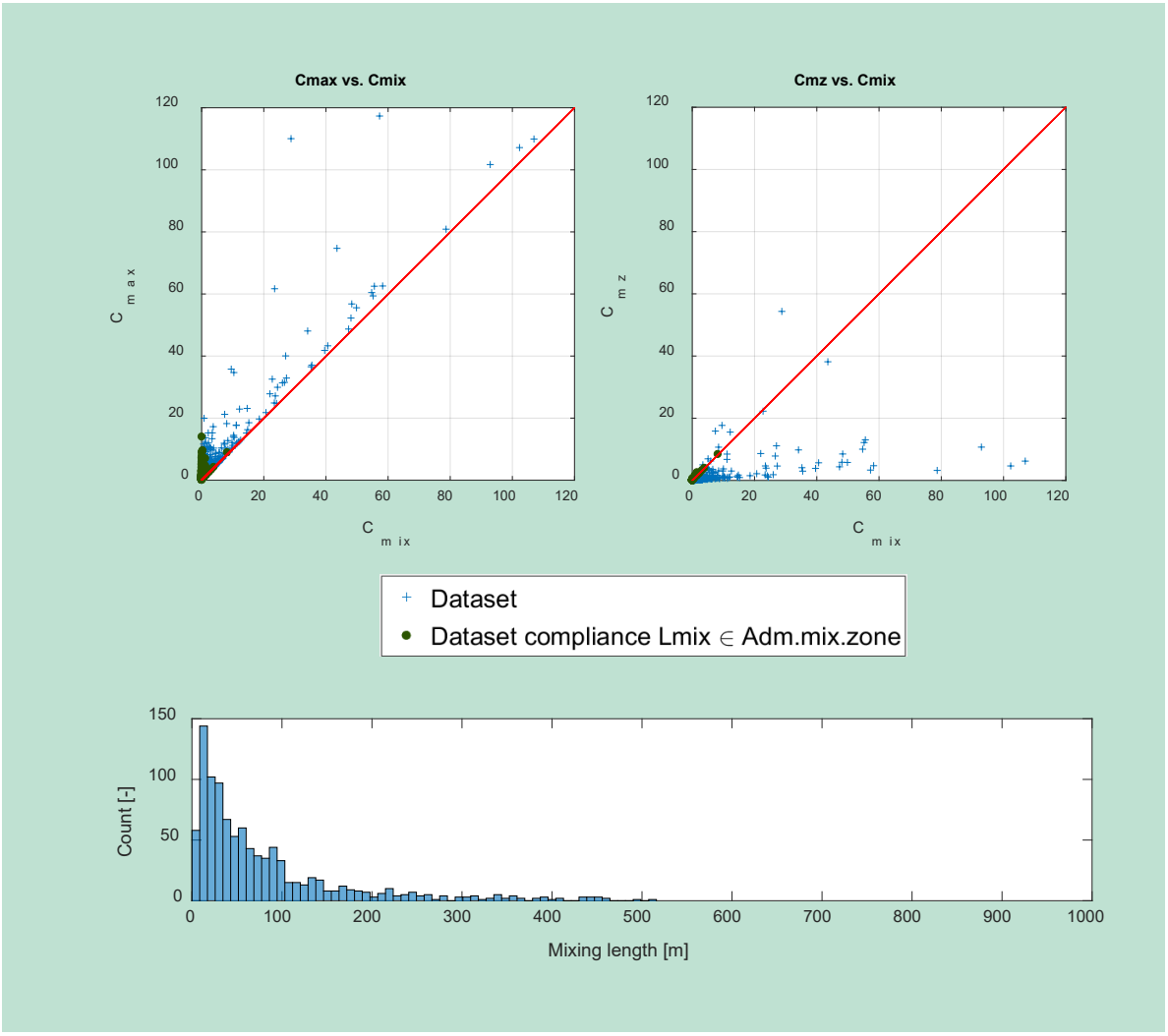

FIGURE 35. MC simulation results for small streams: Evolution of C_{max} compared to C_{mix}, and max. concentration at the limit of the calculated mixing zone C_{mz} compared to C_{mix}. Green marker shows a configuration where L_{mix} is achieved within the calculated mixing zone. Histogram of distribution for the mixing length.

The plot of maximum concentration vs. fully mixed concentration shows that these two concentrations are within the same order of magnitude. It is believed that due to the relatively narrow stream, the fully mixed concentrations are achieved relatively fast and the continuous discharge over the plume width is therefore contributing to a limited increase in C_{max}. The fully mixed conditions are achieved within the calculated mixing zone for only 16% of the configurations (green dots on the plot). A significant difference is, however, observed when looking at the fully mixed conditions compared to the concentration at the edge of the calculated mixing zone. The latter is significantly lower for approximately 80% of the cases. The underlying cause is the relatively low dimension of the calculated mixing zone in case of small streams, compared to the large plume coming from the landfills, and consequently a low contribution of the pollutant discharge at the edge of the calculated mixing zone.

Appendix 9.2 Medium streams

The parameter bounds for the simulation of medium streams are given in Table 17. A collection of 1000 random configurations was chosen and the associated results are presented in Figure 36.

TABLE 18. Upper and lower bound of the different simulation variables.

Parameter	Variation range
W [m]	[2-10]
Q [m3/s]	[0.08-1]
S [-]	0.0005
Plume width [m]	[5-500]
Mass discharge [kg/y]	[100-50000]

The Monte Carlo simulation results indicate that for the 1000 random simulations, only 0.6% were fulfilling the criteria of fully mixed conditions achieved within the calculated mixing zone (green dot markers). The maximum concentration observed at the edge of the plume width is always higher than the fully mixed conditions. Finally, when looking at the maximum concentration observed at the limit of the calculated mixing zone, this concentration is for 70% of the simulations lower than concentration at fully mixed conditions. Similarly to the case of the small streams, this deviation is caused by the location of the calculated mixing zone compared to the width of the plume, as well illustrated by the histogram of plume distribution (Figure 37). For large plumes, an important contribution of the contaminant mass discharge for the part of the plume discharging downstream of the calculated mixing zone, located at a maximum distance of 100 m, is still ongoing.

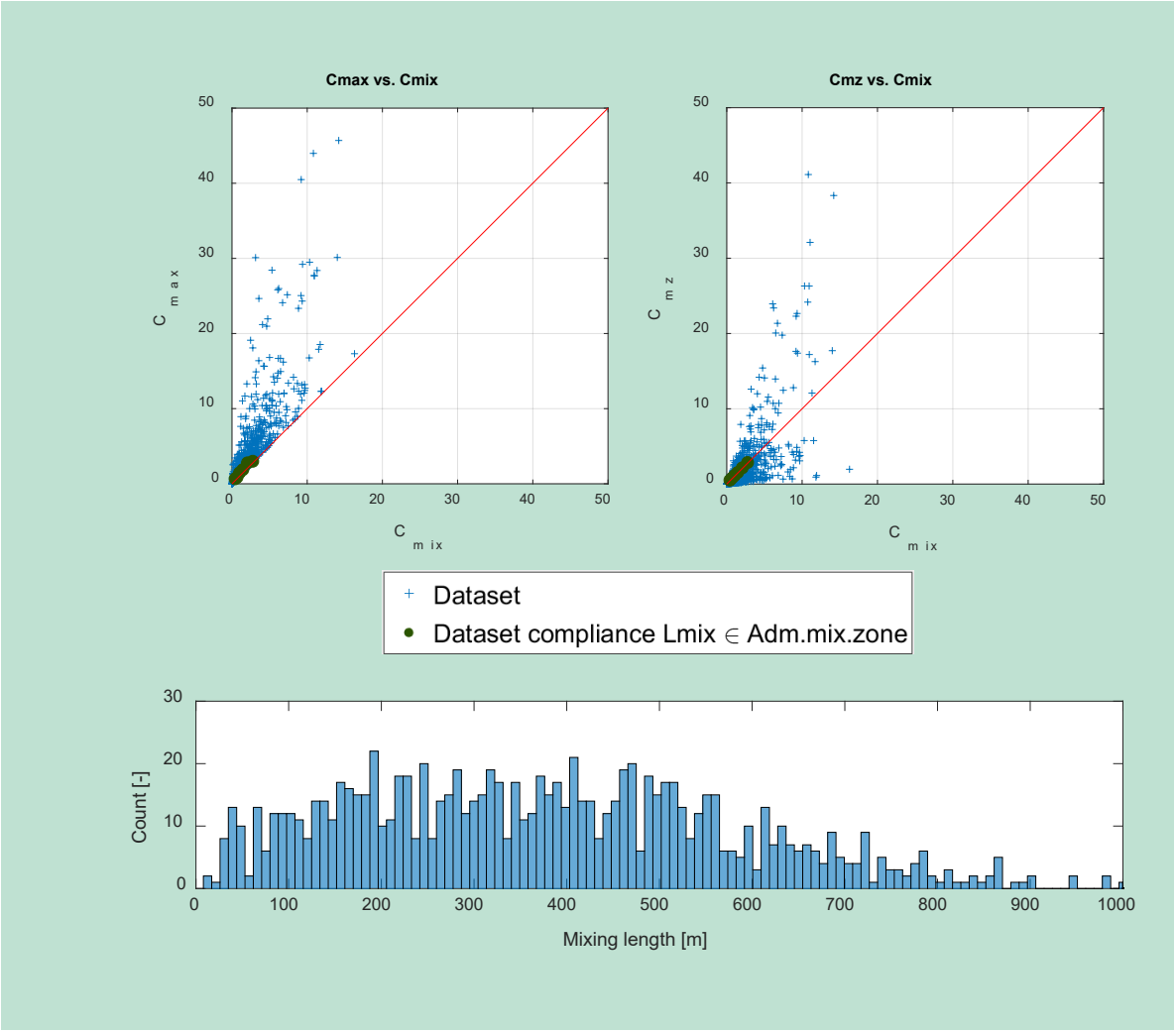

FIGURE 36. MC simulation results for medium streams: Evolution of C_{max} compared to C_{mix}, and max. concentration at limit of the calculated mixing zone C_{mz} compared to C_{mix}. Green markers show a configuration where L_{mix} is achieved within the calculated mixing zone. Histogram of distribution for the mixing length.

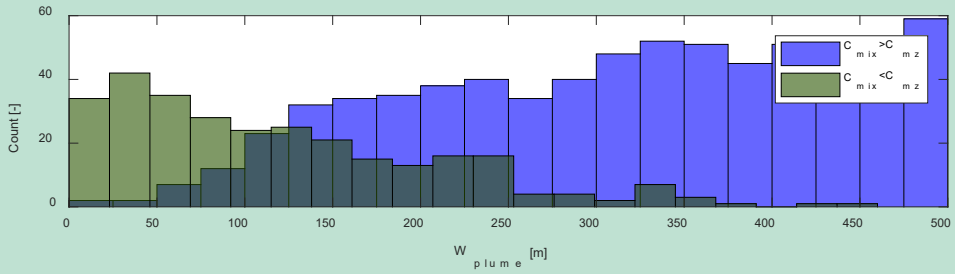

FIGURE 37. Count histogram of plume width for the medium stream simulation. Blue columns: simulations in which $C_{mz} < C_{mix}$. Green columns: $C_{mz} > C_{mix}$.

Appendix 9.3 Large streams

The parameter bounds for the large stream simulations are given in Table 18. Plot of the variables of interest are displayed in Figure 38.

TABLE 169. Upper and lower bound of the different simulation variables.

Parameter	Variation range
W [m]	[10-15]
Q [m3/s]	[2-8]
S	0.0005
Plume width [m]	[5-500]

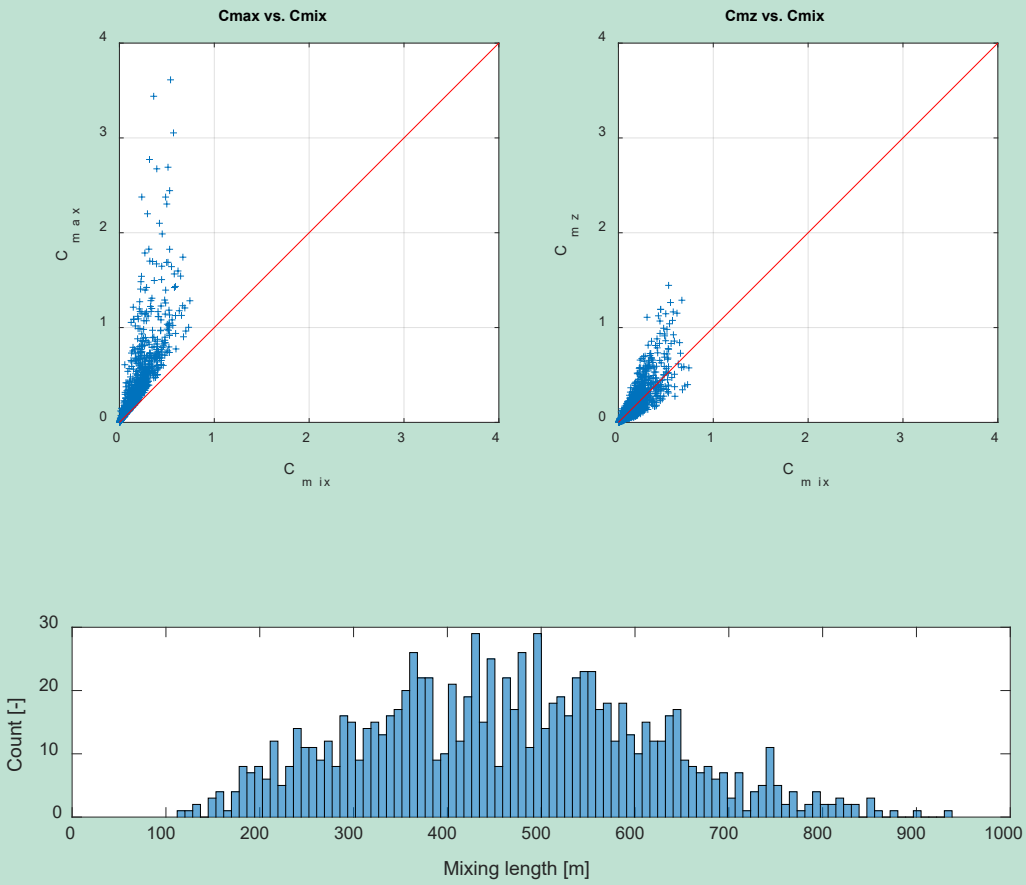

FIGURE 38. MC simulation results for large streams: Evolution of C_{max} compared to C_{mix}, and max. concentration at limit of the calculated mixing zone C_{mz} compared to C_{mix}. Green marker shows a configuration where L_{mix} is achieved within the calculated mixing zone. Histogram of distribution for the mixing length.

For the large stream configuration. it was impossible to find a configuration where the fully mixed conditions are achieved within the calculated mixing zone, i.e. mixing always occurs beyond 100 m from the upstream edge of the plume. As for the medium stream cases, the max. concentration is always higher than the fully mixed concentration in the large streams. All concentrations are lower than the ones obtained in small and medium streams and driven by more important dilution factors The variations in the maximum concentration at the edge of the calculated mixing zone compared to the fully mixed concentration are, however, relatively limited, and there is no noticeable trend (51% of the simulations result in C_{mz} less than the fully mixed concentrations).

Methodology for risk assessment of stream water contamination by landfills - Mixing of landfill leachate plumes in streams

The Danish Environmental Protection Agency has in collaboration with the Danish Waste Association and DepoNet, completed a project with the purpose of developing a methodology for visualizing the site-specific contamination of ground water, surface waters and nature surrounding Danish landfills. The methodology includes description of the contaminant source, transport of contaminants in and above the saturated zone as well as evaluation of the environmental impact.

This report describes the processes in play when a leachate plume originating from a landfill disperses and dilutes in streams. Furthermore, a general methodology is proposed for appointing point of compliance (POC) in the stream for comparison with relevant environmental quality standards (EQS). The estimation of contaminant concentration in stream waters originating from a landfill leachate plume can be handled using an analytical mixing/dilution model. The model Dimicon was developed for this purpose by The Technical University of Denmark. The data input for the model is the output from a transport model of the contaminant in the aquifer (e.g. GrundRisk Landfill). Limitations and assumptions of the Dimicon model are described in this report. The model gives the concentration of contaminants in each grid between plume discharge into the stream and fully mixed conditions.

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