Estimation of Greenhouse Gas Emissions from On-Site Wastewater Management in Switzerland

Study Report

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Résumé (en français)

En Suisse, seuls 2,7% environ de la population ne sont actuellement pas connectés au réseau d'égouts public. Ces 2,7% peuvent être classés en deux catégories : i) les exploitations agricoles qui collectent leurs eaux usées avec les effluents d'élevage, et ii) les bâtiments résidentiels dotés de solutions d'assainissement sur site, ou décentralisées telles que des mini-stations d'épuration (mini-STEP) ou fosses septiques.

Jusqu'à présent, les inventaires d'émissions de gaz à effet de serre provenant de la gestion des eaux usées en Suisse ont uniquement pris en compte les systèmes publics, c'est-à-dire les systèmes municipaux et industriels d'assainissement, de traitement d'eaux usées et de gestion des boues. Jusqu'ici, les systèmes d'assainissement sur site et décentralisés n'ont pas été considérés. Cela repose sur l'hypothèse que 2,7% des systèmes d'assainissement gérés sur site ne contribuent pas de manière significative aux émissions de gaz à effet de serre, en raison des températures basses de l'eau qui préviennent la génération de méthane (CH_4). Cette hypothèse est toutefois discutable, étant donné que les températures ne sont pas en permanence basses, surtout pendant les mois d'été et dans les zones de basse altitude.

Les lignes directrice du Groupe d'Experts Intergouvernemental sur l'Evolution du Climat (GIEC) pour les inventaires nationaux de gaz à effet de serre concernant les émissions provenant du traitement et du rejet des eaux usées sont encore assez limitées en ce qui concerne la gestion des eaux usées sur site dans un pays montagneux d'Europe centrale comme la Suisse. Les voies de rejet disponibles ne prennent en compte que quelques options technologiques pour le traitement décentralisé des eaux usées. Il est donc nécessaire de mener des recherches pour établir des informations spécifiques à chaque pays pour évaluer de manière adéquate les émissions de gaz à effet de serre.

Prenant en compte ces lacunes, la présente étude évalue la pertinence des émissions de gaz à effet de serre provenant de la gestion des eaux usées sur site en Suisse et établit des estimations quantitatives. En compilant et analysant l'information disponible et existante, cette étude fournit une base pour une quantification plus précise des émissions provenant des systèmes alternatifs dans les zones non raccordées au réseau d'égouts.

Cette recherche estime qu'en 2021, environ 125'000 équivalents-habitants (EH) ont rejeté leurs eaux usées dans les fosses à purin, ce qui correspond à 1,44% de la population suisse. Les 1,26% restants de la population non raccordée au réseau d'égouts (environ 110'000 EH en 2021) étaient desservis par des systèmes d'assainissement sur site. Les émissions de gaz à effet de serre provenant de l'assainissement sur site ne se limitent pas aux 2,7% de la population qui ne sont pas raccordés au réseau d'égouts. Les systèmes de traitement sur site sont plus répandus ; même certaines parties de la population connectées au réseau d'égouts les utilisent, notamment pour le tourisme (c'est-à-dire les propriétaires/utilisateurs de maisons de vacances ou résidences secondaires, les clients de l'hôtellerie, etc., qui ont accès à un raccordement au réseau d'égouts dans leur résidence principale). Cette étude estime qu'actuellement, les eaux usées d'environ 0.7% de la population Suisse raccordée au réseau d'égouts (environ 60'000 EH en 2021) sont gérés dans des systèmes d'assainissement sur site. Il est important de quantifier correctement les émissions correspondantes pour éviter un double comptage et des sous-estimations.

Cette étude présente une première estimation relativement approximative des émissions de CH_4 et N_2O provenant de la gestion des eaux usées sur site en Suisse. Malgré de grandes incertitudes, cette étude présente la meilleure estimation possible qui peut être faite actuellement avec les données disponibles limitées. Elle souligne l'importance des émissions de gaz à effet de serre qui y sont liées, et qui ont été négligées jusqu'à présent, étant donné que plus de 97% de la population suisse est connectée à des systèmes centralisés.

Des données sur la température de l'eau provenant des mini-STEP du canton de Schwytz montrent que l'hypothèse précédente selon laquelle aucun gaz à effet de serre n'est émis par les systèmes d'assainissement sur site en Suisse n'est pas correcte, et que les petits systèmes doivent être pris en compte dans l'inventaire. De fait, on peut supposer que les émissions de CH_4 et N_2O provenant des systèmes d'assainissement autonomes se produisent tout au long de l'année, bien que dans une moindre mesure en hiver.

Les deux gaz sont très importants, mais le CH_4 est généralement plus important que le N_2O : en 2019, on estime que le CH_4 a contribué à 59% et le N_2O à 41% des émissions de gaz à effet de serre de l'assainissement sur site en équivalent CO_2. Cela peut surprendre, étant donné le facteur d'émission du N_2O très élevé suggéré pour les STEP aérobies (0,08 kg N_2O-N/kg N) et le potentiel de réchauffement climatique du N_2O étant presque 10 fois plus élevé que celui du CH_4. Toutefois, l'importance du CH_4 devient claire si l'on considère que la quasi-totalité des systèmes actuels d'assainissement sur site comportent une étape de traitement primaire anaérobie avec de longs temps de séjour, ce qui entraîne une méthanogenèse substantielle. L'estimation suggère que l'assainissement sur site contribue à un pourcentage impressionnant de 16% des émissions totales de CH_4 provenant de la gestion des eaux usées.

Les émissions de gaz à effet de serre des mini-STEP peuvent être très élevées ; beaucoup plus que celles des installations à grande échelle bien contrôlées. Les facteurs d'émission peuvent toutefois varier considérablement en fonction de la technologie utilisée. Il est donc recommandé d'examiner plus en détail les émissions de gaz à effet de serre provenant du traitement des eaux usées à petite échelle. En particulier, compte tenu de l'émergence de nouvelles technologies (par exemple, les lombrifiltres pour le traitement primaire aérobie, la séparation des urines) qui peuvent réduire considérablement les émissions de gaz à effet de serre (par exemple, en évitant autant que possible la digestion anaérobie ou la nitrification instable), l'élaboration de politiques pourrait orienter la gestion des eaux usées sur site en Suisse vers une approche plus respectueuse du climat. Bien que le traitement décentralisé des eaux usées (sans tenir compte des exploitations agricoles reliées à des réservoirs à lisier) n'offre une solution d'assainissement tout au long de l'année qu'à environ 1,3% de la population suisse, l'assainissement autonome contribue à plus de 7% des émissions globales de gaz à effet de serre (exprimées en équivalent CO_2) provenant du traitement des eaux usées. Par conséquent, un choix judicieux de la technologie peut améliorer l'impact climatique de la Suisse à l'avenir.

Les autorités cantonales pourraient être en mesure de fournir des données supplémentaires pertinentes. Les études futures devraient donc les impliquer plus étroitement. Des recherches supplémentaires sont nécessaires pour réduire les incertitudes actuelles. Ainsi, une attention particulière devrait être mise sur la manière de suivre l'évolution temporelle du mix de technologies pour les quantifications futures de gaz à effet de serre.

Les données sur les émissions des systèmes à petite échelle des procédés conventionnels de traitement aérobie des eaux usées font défaut dans le contexte de la Suisse. Des campagnes de mesures supplémentaires sont nécessaires pour confirmer si les facteurs d'émissions sont réellement aussi élevés que suspectés, en comparant plusieurs systèmes et conditions de fonctionnement (y compris les régimes de température). Seules des données d'échantillonnage détaillées permettraient de mieux établir les liens entre la conception, l'exploitation et les émissions, afin d'obtenir des données solides pour les inventaires de gaz à effet de serre et pour des recommandations de politiques respectueuses du climat.

Zusammenfassung (auf Deutsch)

In der Schweiz sind derzeit nur etwa 2.7 % der Bevölkerung nicht an die öffentliche Kanalisation angeschlossen. Diese 2.7 % lassen sich unterteilen in i) landwirtschaftliche Betriebe, die ihr Abwasser zusammen mit Gülle sammeln, und ii) Wohngebäude mit vor Ort installierten dezentralen Sanitärsystemen wie Kleinkläranlagen (KLARA) oder Sickergruben.

Bislang wurden im Treibhausgasinventar der Schweiz bezüglich Abwasserbehandlung nur öffentliche Systeme berücksichtigt, sprich die kommunale und industrielle Kanalisation, die zentralisierte Abwasserreinigung und die Schlammbehandlung. Das bedeutet, dass Treibhausgas (THG) - Emissionen von dezentralisierten Abwassersystemen nicht miteinbezogen wurden. Es wurde bisher angenommen, dass die 2.7% des Abwassers, die vor Ort behandelt werden, nicht wesentlich zu den THG-Emissionen beitragen. Dem unterliegt die Annahme, dass das Wasser genügend kühl ist, um die Produktion von Methan (CH_4) zu unterbinden. Wegen der hohen Temperaturen im Sommer und in Anbetracht dessen, dass gewisse KLARA in tiefen Höhenlagen liegen, ist jedoch fraglich, ob die Wassertemperaturen tatsächlich durchgehend genügend tief sind.

Die aktuellen Richtlinien des Weltklimarats (IPCC) für nationale Treibhausgasinventare sind noch begrenzt in Bezug der Emissionen aus der Abwasserbehandlung und -einleitung von dezentralen Systemen aus bergigen, zentraleuropäischen Ländern wie der Schweiz. Die verfügbaren Daten beschränken sich auf wenige dezentrale Technologien. Aus diesem Grund braucht es weitere Forschung, um länderspezifische Informationen über die geschätzten THG-Emissionen aus KLARA zu ermitteln.

In Bezug auf diese Forschungslücke untersucht die vorliegende Studie die Relevanz von THG-Emissionen, die aus vor Ort installierten Abwassersystemen der Schweiz resultieren. Es wurden quantitative Schätzungen vorgenommen: Verfügbare Informationen wurden analysiert und zusammengetragen, um eine Grundlage für eine präzisere Quantifizierung der Emissionen von alternativen Abwassersystemen zu bilden.

Diese Studie schätzt, dass im Jahr 2021 das Abwasser von rund 125'000 Einwohnergleichwerten (EW), was 1.44% der Schweizer Bevölkerung entspricht, in Güllegruben eingeleitet wurde. Das Abwasser der verbleibenden 1.26% der Bevölkerung ohne Kanalisationsanschluss (ca. 110'000 EW im Jahr 2021) wurde in Abwassersystemen vor Ort behandelt. Jedoch beschränken sich dezentrale Systeme und daraus entstehende THG-Emissionen nicht nur auf die zuvor genannten 2.7% der Bevölkerung. Auch Bevölkerungsteile, welche an die Kanalisation angeschlossen sind, nutzen lokale Abwassersysteme, vor allem im Tourismus: Manche Menschen sind in ihrem festen Wohnsitz zwar an das öffentliche System angeschlossen, nutzen in Gastbetrieben, Ferien- oder Zweitwohnungen aber dezentrale Abwassersysteme. Demnach schätzt die vorliegende Studie, dass das Abwasser von 0.7% der schweizerischen Bevölkerung (etwa 60'000 EW im Jahr 2021) mit Kanalisationsanschluss teilweise in KLARA aufbereitet wird. Es ist wichtig, die daraus entstehenden Emissionen genau zu quantifizieren, um sowohl Doppelerfassungen wie auch Unterschätzungen zu vermeiden.

Diese Studie präsentiert eine erste, relativ grobe Schätzung der Methan- (CH_4) und Lachgas- (N_2O) Emissionen aus der dezentralen Abwasserreinigung in der Schweiz. Es sind die bestmöglichen Schätzungen, die basierend auf den begrenzten verfügbaren Daten und trotz der grossen Unsicherheiten gemacht werden können. Aufgezeigt wird, dass die THG-Emissionen aus dezentralen Abwassersystemen relevant sind, obwohl sie bisher vernachlässigt wurden, da mehr als 97% der Bevölkerung an die Kanalisation angeschlossen sind.

Die Wassertemperaturdaten von KLARA im Kanton Schwyz zeigen, dass die bisherige Annahme, dass in der Schweiz keine THG aus dezentralen Abwassersystemen emittiert werden, nicht korrekt ist. Auch kleine Systeme müssen im

Treibhausinventar berücksichtigt werden. Es kann nämlich davon ausgegangen werden, dass sowohl CH_4- als auch N_2O-Emissionen bei KLARA das ganze Jahr über auftreten, wenn auch in geringerem Ausmass im Winter.

Zwar wurden beide Gase als relevant eingestuft, jedoch wird CH_4 insgesamt als bedeutender als N_2O erachtet: Gemessen in CO_2-Äquivalenten (CO_2-eq) trug CH_4 schätzungsweise 59% und N_2O 41% zu den 2019 entstandenen THG-Emissionen in dezentralen Abwassersystemen bei. Dies mag erstaunen, da für aerobe KLARA ein hoher Emissionsfaktor für N_2O anzunehmen ist (0,08 kg N_2O-N/kg N), und angesichts dessen, dass das Treibhausgaspotential von N_2O fast zehnmal höher ist als jenes von CH_4. Die Bedeutung von CH_4 wird jedoch dann deutlich, wenn berücksichtigt wird, dass praktisch alle heutigen dezentralen Abwassersysteme eine anaerobe Erstbehandlungsstufe mit langen Aufenthaltszeiten haben, was zu einer erheblicher Methanogenese führt. Die Schätzung legt nahe, dass dezentrale Abwassersysteme zu beeindruckenden 16% der gesamten CH_4-Emissionen aus der Abwasserentsorgung beitragen.

Die THG-Emissionen von KLARA können viel höher sein als jene von sorgfältig kontrollierten Grossanlagen. Die Emissionsfaktoren der entsprechenden Gase können aber je nach Technologie stark variieren. Daher wird empfohlen, THG-Emissionen aus Kleinkläranlagen vertieft zu untersuchen. Insbesondere im Hinblick auf neue Technologien (z.B. Wurmfilter für die aerobe Erstbehandlung oder Urintrennung), die die THG-Emissionen erheblich reduzieren können (z.B. durch weitgehende Vermeidung von anaerober Vergärung oder instabiler Nitrifikation), könnte die Politik die dezentrale Abwasserbehandlung in der Schweiz klimafreundlicher ausrichten. Obwohl die dezentrale Abwasserbehandlung (ohne Berücksichtigung der an Güllegruben angeschlossenen landwirtschaftlichen Betriebe) nur für ca. 1.3 % der Schweizer Bevölkerung eine ganzjährige Sanitärlösung darstellt, trägt die Abwasserbehandlung vor Ort mehr als 7% zu den gesamten Treibhausgasemissionen (in CO_2-eq) aus der Abwasserbehandlung bei. Es gibt also Potential, die Klimabilanz der Schweiz in Zukunft mit geschickter Technologieauswahl zu verbessern.

Künftige Studien sollten die kantonalen Behörden stärker einbeziehen, da diese möglicherweise zusätzliche relevante Daten liefern können. Weitere Studien sind erforderlich, damit die Unsicherheiten verringert werden können. Dabei sollte ein Schwerpunkt darauf liegen, wie die zeitliche Entwicklung des KLARA-Technologie-Mixes in künftigen THG-Quantifizierungen erfasst werden kann.

Derzeit fehlen Emissionsdaten zur konventionellen aeroben Abwasserreinigung in KLARA in der Schweiz. Weitere Messkampagnen sind erforderlich, um herauszufinden, ob die Emissionsfaktoren so hoch sind wie vermutet, wobei mehrere Systeme und Betriebsbedingungen (einschliesslich unterschiedliche Temperaturregimes) verglichen werden sollten. Nur eine detaillierte Datenerfassung kann dazu beitragen, die Zusammenhänge zwischen Art der Anlage, Betrieb und Emissionen weiter zu ergründen, um so zuverlässige Erkenntnisse für das Treibhausgasinventar zu erhalten, welche in eine klimafreundliche Gesetzgebung einfliessen können.

Executive Summary

In Switzerland, only about 2.7% of the population are currently not connected to public sewer networks. The 2.7 % can be further classified as i) farms which collect their sewage together with animal manure and ii) residential buildings with on-site and decentralised sanitation solutions such as small-scale wastewater treatment plants (SSWWTPs) or septic tanks.

To date, the inventories of greenhouse gas (GHG) emissions from wastewater management in Switzerland have taken into account the public systems only, i.e., the municipal and industrial sewerage, wastewater treatment and sludge management systems. So far, on-site and decentralised wastewater management systems have not been considered. This is based on the assumption that the 2.7% of wastewater managed on-site does not contribute significantly to the GHG emissions due to low water temperatures which prevent the generation of methane (CH_4). This assumption is, however, questionable, as temperatures are not constantly low, especially during summer months and in lower-lying areas.

The current Intergovernmental Panel on Climate Change (IPCC) guidelines for national GHG inventories on emissions from wastewater treatment and discharge are still quite limited regarding on-site wastewater management in a mountainous central European country like Switzerland. The available discharge pathways consider only few technology options for decentralised wastewater treatment, so there is a need for research to establish country-specific information to adequately estimate GHG emissions.

Acknowledging these gaps, the present study assesses the relevance of GHG emissions from on-site wastewater management in Switzerland and makes quantitative estimates. By compiling and analysing available, existing information, the study lays a foundation for a more precise quantification of the emissions from alternative systems in non-sewered areas.

This research estimates that in 2021 about 125’000 population equivalents (PE) discharged their wastewater into manure tanks, corresponding to 1.44% of the Swiss population. The remaining 1.26% of the population without sewer connection (about 110’000 PE in 2021) were served by on-site sanitation systems. GHG emissions from on-site sanitation are not limited to the 2.7% of the population that do not have a sewer connection. On-site systems are more widespread – even parts of the population connected to sewers are using them, particularly for tourism (i.e., owners/users of holiday houses/secondary residences, guests at hospitality services etc. who have access to a sewer connection at their permanent residence). This study estimates that currently the wastewater of about 0.7% of the Swiss population with a sewer connection (about 60’000 PE in 2021) is managed in on-site systems. It is important to properly quantify the corresponding emissions to avoid double counts and underestimates.

This study presents a first, relatively rough estimate of CH_4 and N_2O emissions from on-site wastewater management in Switzerland. Despite high uncertainties, the study presents the best possible estimation that can currently be made using the limited data available. It highlights the importance of the related GHG emissions which have previously been neglected, given that more than 97% of the Swiss population are connected to centralised systems.

Water temperature data from SSWWTPs in the canton of Schwyz shows that the previous assumption that no GHG are emitted from on-site sanitation systems in Switzerland is not correct, and that small systems need to be taken into consideration in the inventory. In fact, it can be assumed that emissions of both CH_4 and N_2O from on-site systems occur throughout the entire year, although to a lesser extent in winter time.

Both gases are found to be very relevant, but CH_4 has a higher overall importance than N_2O: in 2019, CH_4 contributed an estimated 59% and N_2O 41% of on-site sanitation's GHG emissions in CO_2eq. This might astonish, given the very high N_2O emission factor suggested for aerobic SSWWTPs (0.08 kg N_2O-N/kg N) and the global warming potential of N_2O being almost 10 times higher than that of CH_4. However, the importance of CH_4 becomes clear when considering that practically all of today's on-site sanitation systems include an anaerobic primary treatment stage with long residence times, leading to considerable methanogenesis. The estimate suggests that on-site sanitation contributes an impressive 16% of the total CH_4 emissions from wastewater management.

GHG emissions from SSWWTPs can be very high – much higher than from well-controlled large-scale facilities. Emission factors, however, can differ considerably, depending on the technology. It is therefore recommended to further examine the GHG emissions from small-scale wastewater treatment. Especially in the view of emerging novel technologies (e.g., vermifilters for aerobic primary treatment, urine-diversion) which can considerably reduce GHG emissions (e.g., by avoiding anaerobic digestion or unstable nitrification as much as possible), policy making may direct on-site wastewater management in Switzerland towards a more climate-friendly approach. Although decentralised wastewater treatment (without considering farms connected to liquid manure tanks) provides a year-round sanitation solution to only approx. 1.3% of the Swiss population, on-site sanitation contributes more than 7% of the overall GHG emissions (expressed in CO_2eq) from wastewater treatment. Therefore, a wise technology selection may improve Switzerland's climate impact in the future.

The cantonal authorities may be able to provide additional relevant data. Future studies should therefore involve the cantonal authorities more closely. Further investigations are needed to reduce the current uncertainties. Thereby, a focus should be on how to keep track of the temporal evolution of the technology mix for future GHG quantifications.

Emission data on small-scale systems of conventional aerobic wastewater treatment processes have been lacking for the context of Switzerland. Further measurement campaigns are needed to confirm if the emission factors are actually as high as suspected, comparing multiple systems and operating conditions (including temperature regimes). Only detailed sampling data would help to further establish the connections between design, operation and emissions in order to come up with robust inputs for the GHG inventories and climate-friendly policy recommendations.

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Abbreviations

BOD	Biochemical Oxygen Demand
CO_2eq	CO_2 Equivalent
COD	Chemical Oxygen Demand
EF	Emission Factor
GHG	Greenhouse Gas
HSSF	Horizontal Subsurface Flow
IPCC	Intergovernmental Panel on Climate Change
MBBR	Moving Bed Biofilm Reactor
MBR	Membrane Bioreactor
MCF	Methane Correction Factor
PE	Population Equivalent
RBC	Rotating Biological Contactor
SBR	Sequencing Batch Reactor
SSWWTP	Small-Scale Wastewater Treatment Plant
VSSF	Vertical Subsurface Flow
WWTP	Wastewater Treatment Plant

1 Introduction

1.1 Greenhouse gas emissions from wastewater management

1.1.1 Greenhouse gases emitted from wastewater management processes and their relevance

Linked to sanitation and wastewater management, greenhouse gases (GHG) are generated and released mainly in the following processes:

- Production of nitrous oxide (laughing gas, N_2O)
  - Generated as a by-product of nitrification, or an intermediate product of denitrification, N_2O is emitted mainly during the aeration in the biological treatment stage but also in unaerated zones, secondary clarifiers and receiving waterways (Gruber et al., 2022; Gruber, Joss, et al., 2021; IPCC, 2019).
  - The incineration of sewage sludge can also cause high emissions if not well operated (Gruber, von Känel, et al., 2021)
- Production of methane (CH_4)
  - In sewer systems (less relevant in on-site wastewater management)
  - In water treatment units with anaerobic conditions. In conventional wastewater treatment plants (WWTP), the biological treatment step is the most important emission source, as the dissolved methane gets stripped to the air during aeration (Gruber, Joss, et al., 2021; IPCC, 2019).
  - During the anaerobic digestion of sludge (i.e., during treatment and storage of sludge)
- [Production of carbon dioxide (CO_2)]
  - Direct emissions from the decomposition of carbon compounds: not relevant for the GHG inventory due to its biogenic nature (IPCC, 2019).
  - Emissions caused by power consumption: according to the IPCC guidelines, these emissions are not accounted to the waste sector.

Annex 1 provides a brief description of the GHG emission potentials of various wastewater and sludge management processes.

CH_4 and N_2O contribute an important share of the GHG emissions in Switzerland. In 2019, CH_4 and N_2O accounted for 10.1% and 6.7%, respectively, of all Swiss GHG emissions in CO_2 equivalents (FOEN, 2021). In the same year, the waste sector (including wastewater management) contributed approx. 11% of all methane emissions, and 7% of the N_2O emissions (FOEN, 2021). Overall, the GHG emissions from the waste sector are decreasing. This is mainly due to the decrease in the emissions from solid waste disposal. A reduction is also observed for N_2O emissions from wastewater treatment and discharge since 1990, due to improved nitrogen removal rates at WWTP (Gruber, Joss, et al., 2021). The CH_4 emissions from wastewater treatment and discharge, however, have been slightly increasing in Switzerland. This is because of the increase in population (Gruber, Joss, et al., 2021). Due to its global warming potential and emitted quantities, N_2O today still represents the most important GHG emitted from wastewater treatment (Gruber et al., 2022). According to the most recent research findings, N_2O emissions from Swiss WWTP amounted to approx. 1% of the total Swiss GHG emissions and about 20% of the Swiss N_2O emissions in 2019 (Gruber et al., 2022). Note that the latter findings are included as planned improvement in the 2022 Swiss National Inventory Report (FOEN, 2022).

1.1.2 Factors governing the generation of N_2O and CH_4 from wastewater management

The following factors are relevant for the emission of **N_2O** from wastewater management:

- Many factors affect N_2O emissions, including the temperature and dissolved oxygen concentration of the wastewater, and the specific operational conditions (IPCC, 2019).
- The treatment technology itself does not have a direct influence on the N_2O emission factor (Vasilaki et al., 2019).
- Denitrifying WWTPs tend to have lower N_2O emissions than plants that are only designed for nitrification and/or carbon removal (Gruber et al., 2022). High nitrogen removal performance generally helps to lower the N_2O emissions. The optimisation of denitrification processes contributes to reducing the release of N_2O (Gruber et al., 2022).
- An unstable nitrification and related nitrite accumulation represents an important driver for N_2O emissions (Gruber et al., 2022). While the reasons for nitrite accumulation are not yet well understood, there is evidence that insufficient aeration and strong (seasonal) fluctuations of the operating conditions (e.g., temperature drops – see below, changing loads or utilisation patterns) are problematic for nitrite oxidation and can cause high N_2O emissions (Gruber et al., 2020; Gruber, Niederdorfer, et al., 2021). Figure 1 roughly shows how the emission factor behaves in conventional WWTPs depending on the stability of the nitrification and the denitrification performance.
- Low temperatures (linked to altitude and exposure to sunlight, among others) can inhibit both nitrification and denitrification (Zhou et al., 2018). At water temperatures below 10°C, nitrification is very limited (Kim et al., 2006). At about 5°C, nitrifying bacteria practically cease functioning (Tchobanoglous et al., 2004). According to Gruber, von Känel, et al. (2021), large amounts of N_2O can be emitted particularly when the temperature sinks to a level where nitrification is inhibited and becomes unstable. Similarly, denitrification is also decelerated and incomplete at low temperatures, causing the generation of N_2O (Massara et al., 2017).
- In general, good process control (including monitoring) helps to maintain stable and favourable conditions.

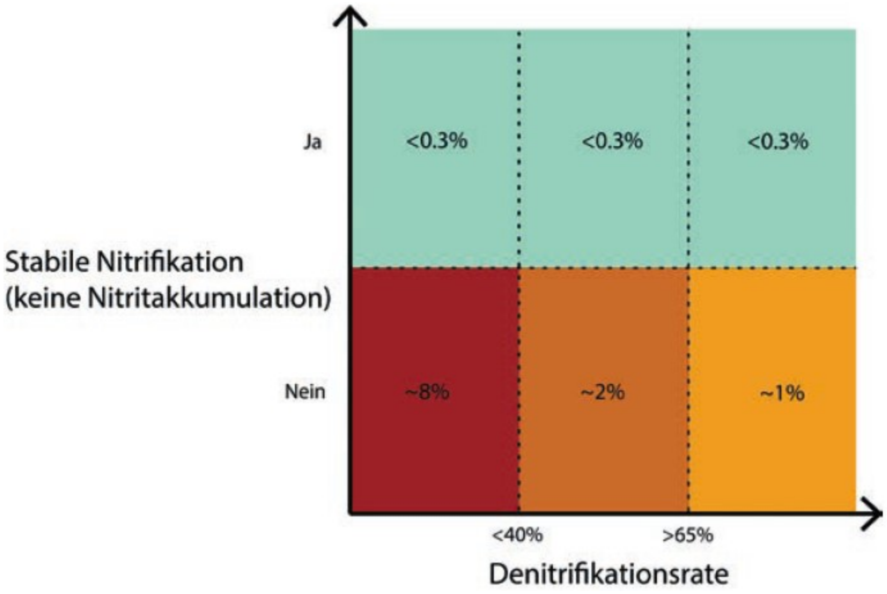

Figure 1: *Rough estimation of the N_2O emission factors (in percent kg N_2O-N / kg $N_{influent}$) from the biological treatment stage in conventional WWTP, as a function of the nitrification stability and denitrification rate (Source: Gruber et al., 2022)*

The following factors are relevant for the emission of **CH_4** from wastewater management:

- Temperature (linked to altitude and exposure to sunlight, among others): the optimal temperature for anaerobic digestion is at 30-38°C. At lower temperatures, the process becomes slower and CH_4 production becomes unlikely below 12°C (IPCC, 2019). While low temperatures can prevent CH_4 emissions, they may also just lead to seasonal fluctuations of anaerobic activity and gas release, especially in small-scale systems (see section 1.2.1).
- Residence time of water and sludge in oxygen-deficient system components: a higher residence time in a place with insufficient oxygen supply will lead to increased degradation processes under anaerobic conditions and the generation of higher amounts of CH_4. Sludge removal and the hydraulic system load are processes which affect the residence time.
- Process design and control: anaerobic conditions may occur in unintended ways if a system is poorly designed or not well maintained and operated.

1.2 Greenhouse gas emissions from on-site wastewater management

On-site wastewater management is here defined as a solution for the collection, treatment and/or disposal of used water at or near its point of generation, without the connection to a public sewer network. On-site wastewater management systems are often called decentralised or small-scale sanitation systems.

1.2.1 GHG emissions: differences between large-scale and small-scale (on-site) systems

Compared to large-scale (centralised) systems, on-site wastewater management systems have the following characteristics that affect their GHG emissions:

- Only short piping systems: negligible emissions in sewers, therefore possibly higher emission factor (EF) for CH_4 in primary treatment units.
- Anaerobic primary treatment: often higher residence times and sludge stabilisation already there, due to infrequent sludge removal. Possibly higher methane emissions in the primary settling tank, less stripping during aeration steps.
- Aerobic primary treatment and solids composting possible in certain designs, which leads to less methane emissions from primary sludge and in secondary treatment stages (Alternative Carbone, 2019).
- Systems are often underground and covered, making them less responsive to air temperature changes than open systems. Depending on the design, temperature fluctuations within the system would correlate well with the soil temperature, which is more constant than air temperature.
- On the other hand, temperature fluctuations in small systems can have a relevant effect: *“Inside septic tanks, the temperature is uncontrolled and is related to atmospheric temperature as well as volumes of household hot and cold water used and discharged. There may also be a gradient of temperature inside the septic tank, with warmer conditions at the bottom (sludge layer) and colder at the top (Leverenz et al. 2010). Therefore, in countries having seasonal temperature variability, when the temperature in septic tanks cools, the rate of digestion slows, the solids retention time increases, sludge accumulates, and CH_4 emissions decrease. When the liquid temperature warms, the rate of digestion increases, sludge accumulated during the cold season decomposes, gas solubility in the liquid decreases and CH_4 emissions increase. This situation can produce a ‘spring boil’ phenomenon, wherein warmer weather conditions give rise to increased anaerobic microbial activity, increased gas production, and decreased solids removal efficiency due to the resuspension of settled*

and incoming solids. Accordingly, there is a seasonal variability of CH_4 emissions (Leverenz et al. 2010); however, at this time, insufficient data exist to establish a temperature-dependent emission factor associated with these systems. Countries that experience significant seasonal temperature variations may wish to consider the development of a country-specific emission factor." (IPCC, 2019)

- Less process control (e.g., less real-time monitoring of operating or performance parameters) makes it harder to ensure stable nitrification and a well-performing denitrification. This is likely to lead to higher N_2O emissions, especially linked to nitrite accumulation (Gruber, von Känel, et al., 2021; Vogt, 2020).
- Wastewater is more concentrated (less or inexistent dilution by rainwater or industrial activities, water saving lifestyle), which can lead to process instabilities.

1.3 On-site wastewater management in Switzerland and the probable significance of GHG emissions

1.3.1 On-site sanitation in Switzerland

In Switzerland, about 2.7% of the population (i.e., approx. 235'000 persons) are currently not connected to public sewer networks (BAFU, 2021). This fraction is currently assumed to have remained constant since 2011 (BAFU, 2021). Even if the potential to connect to public sewers is nearly exhausted, a slight decrease of the percentage of the population not connected can still be expected in the future because the population growth is taking place predominantly in the urbanised areas.

The 2.7 % can be further classified as i) farms which collect their sewage together with animal manure and ii) on-site and decentralised sanitation solutions:

i) Farms that cannot be connected to public sewer networks and hold at least eight cows or pigs are qualified to connect their domestic wastewater to the liquid manure (slurry) tank and to dispose of the manure and sewage by land application. Related emissions from both manure and wastewater are occurring in agriculture.

ii) Residents that cannot be connected to public networks and rely on on-site or decentralised sanitation solutions, such as septic tanks, holding tanks or small-scale wastewater treatment plants (SSWWTPs)[1]. The sludge accumulating from these systems requires treatment in public wastewater treatment plants. In practice, however, this is not always the case. For instance, buildings in remote areas can be exempt from this rule by cantonal authorities (Chemical Risk Reduction Ordinance ORRChem, Annex 2.6, clause 3.2.3).

The following table describes the typical owners of on-site sanitation solutions in Switzerland.

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[1] See Table 2 for descriptions of the different technologies.

Table 1: *Overview of the typical owners of on-site sanitation solutions in Switzerland.*

Owner	**Typical characteristics**	**Typical utilisation rate (% of the year)**	**Considerations to avoid double counting of emissions** (see methods section 2.2, also concerning differing EF if emission is already accounted for otherwise)
Farm with 8 or more cattle or pigs	Continuous use, connected to manure tank	100%	Part of the 2.7% without sewer connection – inhabitant to be accounted for.
Farm with less than 8 cattle or pigs	Continuous use, needs separate wastewater solution according to current legislation	100%	Part of the 2.7% – no risk of double counting.
Alpine farm	Seasonal use (summer months only)	33-50%	Inhabitant either already accounted for under centralised wastewater management (if connected to sewer during the rest of the year) or via a farm (if connected to manure tank).
Permanent resident in a non-networked area	Continuous use. Including former farm houses, also multiple in a hamlet	100%	Part of the 2.7% – no risk of double counting.
Permanently operated hospitality service in a non-networked area	Includes restaurants and lodges, sanatoria etc. with year-round use	100%	Guests are typically already accounted for under centralised wastewater management. Hosts may be present year-round and are theoretically to be counted as part of the 2.7%.
Seasonally operated hospitality service in a non-networked area	Includes mountain huts, restaurants and lodges, camp grounds, sanatoria etc. with seasonal use, e.g., during summer or winter months only	33-70%	Both guests and hosts are typically already accounted for under centralised wastewater management (permanent residence most likely connected).
Holiday house / secondary residence in a non-networked area	Diverse use patterns, from occasional to seasonal to regular	10-80%	Inhabitant typically already accounted for under centralised wastewater management (permanent residence most likely connected).
Others	Hunting huts, dairy, sports facilities, motorway service areas, power stations, railway buildings, military infrastructure etc.	10-100%	Users typically already accounted for under centralised wastewater management (permanent residence most likely connected).

1.3.2 On-site sanitation technologies typically used in Switzerland and GHG emission potentials

An on-site sanitation system consists of a combination of technologies from the following categories:

- Toilet and collection / storage technologies: user interface and containment
- Primary treatment technologies: the first major stage in wastewater treatment that removes solids and organic matter mostly by the process of sedimentation or flotation (Tilley et al., 2014).
- Secondary treatment technologies: follows primary treatment to achieve the removal of biodegradable organic matter and suspended solids from effluent. Nutrient removal (e.g., phosphorus) and disinfection can be included in the definition of secondary treatment or tertiary treatment[2], depending on the configuration (Tilley et al., 2014).
- Sludge management technologies: dewatering, stabilisation and pathogen reduction of solids generated in any of the above categories.

Table 2 gives an overview of the main on-site sanitation solutions used in rural Switzerland, along with a brief description, sorted by category. The list is not exhaustive. Further technologies and variations exist. However, the latter are considered not to be of significant importance in terms of their occurrence in Switzerland. The table includes a characterisation of the technologies' GHG emission potentials, stating whether the expected CH_4 and N_2O emissions are relevant or negligible, based on the presence/absence of the processes described in section 1.1.1. This is a general,

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[2] Follows secondary treatment to achieve enhanced removal of pollutants from effluent. Tertiary treatment stages are rarely found in on-site systems in Switzerland.

qualitative characterisation of the emission potential, similar to Table 6.1 in IPCC (2019) (see Annex 1). The factors described in section 1.1.2 will affect the actual emissions in a specific context.

SSWWTPs in Switzerland are normally not designed for nutrient removal, as this is not required by the applicable discharge standards. Most designs for secondary treatment are able to nitrify partially, often limited to the warmer months. Due to seasonal variations of the operating conditions and often irregular use patterns, it can be expected that high denitrifying performance is rare. This eventually has implications on the emission factors for N_2O (see sections 1.1.2 and 3.3.2).

Most systems have anaerobic primary treatment stages, which has implications on the emission factors for CH_4. There are some designs in which the raw wastewater goes directly to an aerobic treatment stage (compost filter, vertical flow constructed wetlands, activated sludge with extended aeration). These designs are, however, not (yet) found very frequently.

Table 2: *Overview of key on-site sanitation technologies, their use and importance in Switzerland as well as their GHG emission potentials.*

Technology	**Description**	**Typical use**	**Importance in CH**	**Dominating function**						**Prevalent operating conditions**		**CH_4 emission potential**	**N_2O emission potential**
				Collection / storage	Carbon removal / stabilisation	Partial nitrification	Full nitrification	Denitrification	Dewatering / Drying	Aerobic	Anaerobic/Anoxic		
Toilet and collection / storage technologies													
Pit latrine	Dry toilet with simple pit, possibly ventilated	Rarely found, e.g., in remote farm buildings, simple holiday cabins and mountain huts, often in higher altitude	Low	X							X	**Relevant**	Negligible
Urine-diverting and composting toilet	Dry toilet with separate collection, drainage or absorption of liquids. Drying or composting of solids. Well-designed and operated systems aim to prevent anaerobic conditions.	Relatively rarely used in mountain huts or holiday cabins	Low	X	X				X	X		Negligible	Negligible
Wastewater holding tank	Impervious tank that collects all the wastewater. When full, its contents need to be transported to a WWTP.	Fairly common in remote holiday cabins	**Medium**	X							X	**Relevant**	Negligible
Combined liquid manure (slurry) and wastewater tank	This is a combined holding tank for animal manure and domestic wastewater from the farm. Only allowed for farms with at least 8 cattle or pigs. When full, its contents can be applied on agricultural land.	Very common solution for farms of a certain size	**High**	X							X	**Relevant**	Negligible
Primary treatment technologies													
Septic tank / primary clarifier	Primary treatment unit existing in various designs, including 2 and 3 chamber tanks as well as Imhoff tanks.	Relatively widespread system in a few areas, although no longer considered state of the art as a standalone solution without further treatment and therefore being phased out.	**Medium**		X						X	**Relevant**	Negligible
Compost filter (“Rottebehälter”)	Primary treatment unit with straw, wood chips or similar as filter substrate. Designed to promote aerobic degradation of solids.	Relatively rarely used for hamlets, individual residential buildings or mountain huts.	Low		X				X	X		Negligible (?)*	Negligible

Technology	**Description**	**Typical use**	**Importance in CH**	**Dominating function**						**Prevalent operating conditions**		**CH_4 emission potential**	**N_2O emission potential**
				Collection / storage	Carbon removal / stabilisation	Partial nitrification	Full nitrification	Denitrification	Dewatering / Drying	Aerobic	Anaerobic /Anoxic		
Secondary treatment technologies													
Soil dispersion system	Leach field or similar soil absorption / infiltration system, typically used in combination with a septic tank.	Uncommon	Low		X	(X)					X	Negligible	**Relevant**
Vertical subsurface flow (VSSF) constructed wetland or soil filter	Filter unit, mostly designed as a planted sand bed through which the water trickles before it gets collected in drainage pipes at the bottom. Depending on the design, no primary treatment is needed.	Relatively widespread solution for hamlets or residential buildings, mostly in lower-lying areas.	**Medium**		X	X		(X)		X	(X)	**Relevant** (although lower than in horizontal-flow wetlands)	**Relevant**
Horizontal subsurface flow (HSSF) constructed wetland or soil filter	Planted filter consisting of sand and gravel layers through which the water flows horizontally. The water is invisible as its level is kept below the surface.				X	X		(X)			X	**Relevant**	**Relevant**
Trickling filter	Filter unit with a relatively coarse filter medium, over which the water is distributed or sprayed. It trickles down over the biofilm and gets collected at the bottom of the filter. Requires a secondary clarifier to remove excess solids.	The most common treatment technology in rural, decentralised applications, also in areas where there is no power supply.	**High**		X	X				X		Negligible (?)	**Relevant**
Rotating biological contactor (RBC)	A tank equipped with a rotating drum that is partially submerged in the wastewater. The slow, engine-powered rotation alternatingly exposes the biofilm growing on the drum surface to air and wastewater, ensuring oxygen supply. Requires a secondary clarifier to remove excess solids.	Relatively rarely used in situations with sufficient electricity supply.	Low		X	X				X		Negligible (?)	**Relevant**
Conventional activated sludge plant	An aerated tank in which a concentrated suspended biomass transforms and removes wastewater constituents. Requires a secondary clarifier to settle the activated sludge. Depending on the design, no primary treatment is needed. Includes extended aeration designs.	Very common treatment technology in rural, decentralised applications with sufficient power supply.	**High**		X	X	(X)	(X)		X	(X)	Negligible (?)	**Relevant**

Technology	**Description**	**Typical use**	**Importance in CH**	**Dominating function**						**Prevalent operating conditions**		**CH$_4$ emission potential**	**N$_2$O emission potential**
				Collection / storage	Carbon removal / stabilisation	Partial nitrification	Full nitrification	Denitrification	Dewatering / Drying	Aerobic	Anaerobic /Anoxic		
Secondary treatment technologies (continued)													
Moving bed biofilm reactor (MBBR)	A compact, aerated tank in which an artificial, loose media provides a large surface for biofilm growth. Due to aeration the bed is constantly moving. Requires a secondary clarifier to remove excess solids.	Relatively rarely used.	Low		X	X	(X)			X		Negligible (?)	**Relevant**
Fixed bed biofilm reactors	A compact, aerated tank in which a fixed package of media provides a large surface for biofilm growth. May also be known as submerged aerated fixed-film (SAFF) reactor.	Rarely used.	Low		X	X	(X)			X		Negligible (?)	**Relevant**
Sequencing batch reactor (SBR)	A compact, single tank system in which the wastewater undergoes treatment in batches, following a fill, aerate, settle and decant sequence.	The second most common treatment technology in rural, decentralised applications with sufficient electricity. Increasingly popular.	**High**		X	X	(X)	(X)		X	(X)	Negligible (?)	**Relevant**
Membrane bioreactor (MBR)	An activated sludge tank equipped with fine membranes which filter the treated water and eliminate the need for a secondary clarifier.	Rarely used in situations with sufficient electricity supply and high budget.	Low		X	X	(X)	(X)		X	(X)	Negligible (?)	**Relevant**
Sludge management technologies													
Unplanted Drying Bed	A sand bed designed for sludge dewatering. Dried sludge needs to be removed before applying fresh sludge.	Relatively rarely used in mountain huts	Low						X	X		Negligible (?)	**Relevant** (?)
Planted Drying Bed	A sand bed designed for sludge dewatering and degradation, with plants that maintain permeability. Fresh sludge layers can be added regularly for several years without the need to remove degraded sludge.	Rare or inexistent	Low		(X)				X	X		Negligible (?)	**Relevant** (?)
Bag Dewatering	Sludge dewatering option, in which sludge gets filled in suspended bags.	Relatively rarely used in mountain huts or large cable car stations	Low						X	X		Negligible (?)	Negligible (?)

* a question mark (?) indicates that the assumption would have to be confirmed through measurements in on-site sanitation systems and/or further literature research.

1.3.3 The probable significance of GHG emissions from on-site wastewater management in Switzerland

To date, the inventories of GHG emissions from wastewater management in Switzerland have taken into account the public systems only, i.e., the municipal and industrial sewerage, wastewater treatment and sludge management systems. So far, on-site and decentralised wastewater management systems have not been considered. This is based on the assumption that the 2.7% of wastewater that is managed on-site does not contribute significantly to the GHG emissions, as these are mostly in high altitude and mountainous areas where the low temperature prevents the generation of CH_4. Switzerland's national inventory report for 1990-2019 (FOEN, 2021) states: *"The production of CH_4 in an anaerobic environment is strongly temperature dependent and significant CH_4 production is unlikely below 15°C due to the inactivity of methanogens (IPCC 2006). As in Switzerland alternative systems are typically buried, the wastewater reaches the rather constant temperature of the surrounding soil, approximately corresponding to the mean annual air temperature. At Grono, the warmest place in Switzerland, the mean annual temperature is 12.4°C. Accordingly, in alternative treatment systems the temperature of the wastewater is too low to produce substantial CH_4 emissions."*

The assumption of low water temperatures constantly around the mean annual air temperature is, however, questionable. Many systems are found in lower-lying areas (e.g., farms) and temperatures are not constantly low, especially during summer months (see data in section 3.3.1). In addition, the relatively high temperature of domestic wastewater may further increase the temperature in the primary treatment. For anaerobic tanks this means that the solids collected during the cold period get digested when the temperature rises ("spring boil" phenomenon described in section 1.2.1). Besides the generation of CH_4 from primary treatment, aerobic systems can also generate N_2O, which has a global warming potential (100-year) of 265 (compared to 28 for CH_4) (Myhre et al., 2013). Indeed, according to Gruber, von Känel, et al. (2021), large amounts of N_2O can be emitted particularly during the transition from a nitrifying to a non-nitrifying process, i.e., when the temperature reduces in the winter season and nitrite accumulates due to unstable nitrification (this was documented at the Giubiasco WWTP).

Acknowledging this gap, the present study aims to describe on-site wastewater management in Switzerland with regard to the generation of GHG. It also aims to lay a foundation for a more precise quantification of the emissions from alternative systems in non-sewered areas.

1.4 Purpose and objectives of this study

The current IPCC guidelines for national greenhouse gas inventories on emissions from wastewater treatment and discharge (IPCC, 2019) are still quite limited with regard to on-site wastewater management in a mountainous central European country like Switzerland. The available discharge pathways consider only few technology options for decentralised wastewater treatment (see Annex 2), so there is a need for research to establish country-specific information to adequately estimate GHG emissions.

This study aims to assess the relevance of GHG emissions from on-site wastewater management in Switzerland and to make quantitative estimates. This is done by compiling and analysing available, existing information only. Wherever this is not possible, an approach may be recommended for more detailed investigations. Additionally, the study aims to answer the following specific questions:

- How are the 2.7% characterised that are not connected to public sewers (numbers, farmers vs others, sludge quantities, utilisation and variation during the year)?
- How many installations of the different on-site sanitation technologies exist?
- What are the CH_4 and N_2O emission factors of different on-site sanitation systems?
- Is there any air and soil temperature data from the areas in which on-site sanitation systems are typically being used?
- Is there any temperature data (incl. greywater temperature) from alternative systems that are representative in terms of location, utilisation etc.
- Is there any emission data from representative alternative systems?
- What fraction of the sludge generated in on-site systems is not being treated at municipal WWTPs?
- How can the overall GHG emissions of on-site systems reliably be estimated, including the consideration that some systems have seasonal or occasional use only (avoiding double counts of the contributions of relevant inhabitants)?
- (How) can data be deduced for the period 1990-2021?
- What should be considered for quantifications beyond 2021?

2 Methods

2.1 Overview of the approach

2.1.1 Data collection

Rather than collecting new data through measurements, this study compiles existing information available and relevant for Switzerland with regard to the questions specified in section 1.4. Data sources for this desk study include cantonal repositories as well as existing literature. In all cantons, the departments in charge of small-scale wastewater treatment plants were contacted to gather databases of installations including information on at least type of technology, number of population equivalents (PE) designed for and connected, and altitude. Useable databases were received from 17 out of 26 cantons. In a few cases the data was accompanied by valuable supplemental information on the cantons' practices and current situation regarding on-site wastewater management, or even sampling results (including water temperature data in the case of the canton of Schwyz).

Further details were obtained from the canton of Berne at a later stage, once it was clear that it is the canton with the largest number of systems in its database.

2.1.2 Data analysis and calculations

The calculations (section 3.3) were carried out according to Vol. 5 (Waste), Chapter 6 (Wastewater Treatment and Discharge) of the 2006 IPCC Guidelines for National Greenhouse Gas Inventories (IPCC, 2006) and its 2019 Refinement (IPCC, 2019).

The emissions in CO_2eq were calculated using the global warming potential (GWP, 100-year) values according to Myhre et al. (2013), Table 8.A.1, as in the Fifth Assessment Report of the IPCC: 265 for N_2O and 28 for CH_4.

The uncertainties (section 3.4) were estimated with the help of Tables 2-1 and 2-2 in Kuenen & Dore (2019).

2.2 Avoiding double counts and underestimates of emissions

The wastewater related GHG emissions of 97.3% of the Swiss population are already accounted for in the data for centralised systems. A small fraction of the population connected to public sewers also stay part-time in buildings that are served by on-site systems (i.e., they are non-permanent users of on-site sanitation systems, see considerations in Table 1). This part of the population should not be counted a second time under the population depending on on-site systems. However, the difference resulting from a higher EF of the on-site systems compared to the centralised systems has to be taken into account, if in a relevant order of magnitude.

Thus, the on-site wastewater management systems in Switzerland including the 2.7% of the population not connected to public sewers are to be accounted for as follows:

Table 3: *Allocation of the emissions of different users of on-site sanitation systems*

	Owner of on-site sanitation solution	**Typical on-site sanitation system**
Agriculture (➲ see section 3.1.2)	• Farm with 8 or more cattle or pigs connected to manure tank	Combined liquid manure (slurry) and wastewater tank
Waste (➲ see sections 3.1.3 and 3.3.4)	• Farm with less than 8 cattle or pigs connected to on-site sanitation system • Permanent resident in a non-networked area connected to an on-site system	SSWWTP, septic tank SSWWTP
Double counts and underestimates to be avoided: check order of magnitude of emissions not yet accounted for. If significant, add difference under “waste”. (➲ see section 3.3.5)	• Alpine farm (seasonally operated) connected to manure or septic tank • Hospitality service in non-networked area* • Holiday house / secondary residence in non-networked area • Other (hunting hut, dairy, sports facility, motorway service area, power station, railway building, military infrastructure etc.)	Combined liquid manure (slurry) and wastewater tank, septic tank SSWWTP Holding tank, SSWWTP, septic tank SSWWTP, septic tank

* In a few cases the emissions of the hosts present year-round would have to be allocated to “Permanent resident in a non-networked area connected to an on-site system”. These insignificant quantities are neglected here.

Figure 2 illustrates how the emissions of the various types of users of on-site sanitation solutions are to be counted.

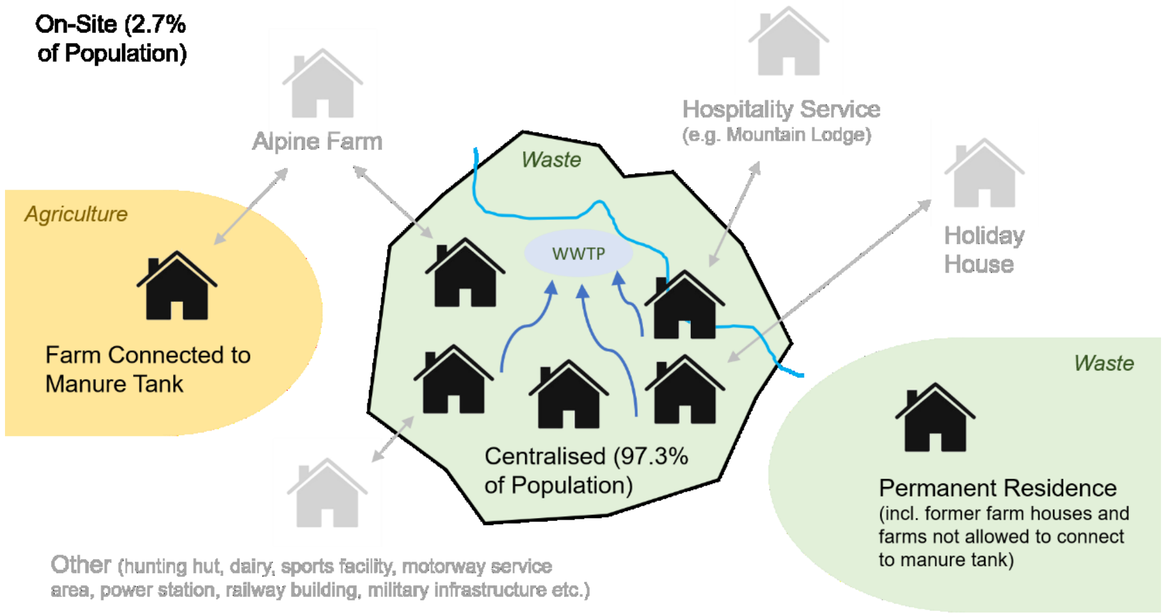

Figure 2: *Illustration of how the GHG emissions of different on-site sanitation users should be allocated to avoid double counts / underestimates of inhabitants. The users shaded in grey (non-permanent users of on-site sanitation) are not to be counted twice; the contributing population is already counted otherwise. However, databases available from the cantons include information mostly on any small-scale wastewater treatment system, without making a distinction on the category of users.*

3 Results

3.1 Estimation of wastewater quantities managed in different on-site sanitation technologies in Switzerland

3.1.1 On-site technologies that are of relevance in Switzerland in terms of CH_4 and/or N_2O emissions

Table 2 in the introduction (section 1.3.2) provides an overview of the on-site sanitation technologies used in Switzerland. According to that table, not all the technologies are relevant in terms of GHG emissions, either because they are rare or because their emission potential is negligible. Table 4 compiles the relevant technologies, considering their occurrence in Switzerland and their emission potentials.

Table 4: *List of on-site technologies that are of relevance in Switzerland in terms of CH_4 and/or N_2O emissions (excludes those technologies that have a low importance due to low occurrence and/or low emission potentials).*

Technology	**Typical characteristics**	**Relevant CH_4 emissions**	**Relevant N_2O emissions**
Toilet and collection / storage technologies			
Wastewater holding tank	Anaerobic, long residence time	X	
Combined liquid manure (slurry) and wastewater tank	Anaerobic, long residence time	X	
Primary treatment technologies			
Septic tank / primary clarifier	Anaerobic, hydraulic retention time may fluctuate depending on use (several hours to several weeks), high solids retention time	X	
Secondary treatment technologies (used in SSWWTP)			
Vertical subsurface flow (VSSF) constructed wetland or soil filter	Carbon removal and partial nitrification, aerobic, with anaerobic primary treatment	X	X
Horizontal subsurface flow (HSSF) constructed wetland or soil filter	Carbon removal and partial nitrification, mostly anaerobic, with anaerobic primary treatment	X	X
Trickling filter	Carbon removal and partial nitrification, aerobic, with anaerobic primary treatment		X
Conventional activated sludge plant	Carbon removal and partial nitrification, aerobic, with anaerobic primary treatment		X
Sequencing batch reactor (SBR)	Carbon removal and partial nitrification, aerobic, with anaerobic primary treatment		X
Remaining aerobic technologies (rotating biological contactor (RBC), moving bed biofilm reactor (MBBR), fixed bed biofilm reactors, extended aeration, and membrane bioreactor (MBR))	Carbon removal and partial nitrification, aerobic, with anaerobic primary treatment		X

Among the **toilet and collection / storage technologies**, the holding tank and the manure tank are common containment solutions. The wastewater quantities collected in holding tanks (and subsequently transported to communal wastewater treatment plants) are currently impossible to estimate (no databases available). However, this is not a big issue, as these tanks are mainly used for holiday houses of which the users are in principle already accounted for under the centralised system (see sections 2.2 and 3.1.3). The manure tanks are of relevance for the emissions related to agriculture. They are, therefore, separately considered and their numbers estimated in section 3.1.2.

Among the **primary treatment technologies**, the septic tank / primary clarifier is a common solution. The difference between the two is that the septic tank is considered a standalone solution which is not connected to further secondary treatment. Here, it is also very difficult to estimate the wastewater quantities collected in septic tanks, as no databases are available in most cantons. Again, this is not a relevant issue, as these tanks are mainly used for buildings of which the users are in principle already accounted for under the centralised system (see sections 2.2 and 3.1.3). Moreover, septic tanks as a standalone solution are no longer considered state of the art and have therefore been phased out in Switzerland for quite some time. Nonetheless, their quantitative relevance is further discussed in section 3.1.3.

Primary clarifiers are settling tanks with a similar function and design as septic tanks, but used in combination with secondary treatment technologies as part of SSWWTPs. Their relevance along with emission factors is further discussed in sections 3.3.2 and 3.3.3.

Among the **secondary treatment technologies** used in on-site wastewater management systems (i.e., SSWWTPs) in Switzerland, trickling filters are the most common, followed by SBRs, conventional activated sludge plants, constructed wetlands (differentiation VSSF/HSSF not possible) and other aerobic technologies (see Figure 3). It can be assumed that almost all systems are built in combination with a primary clarifier (alternatives are still relatively rare).

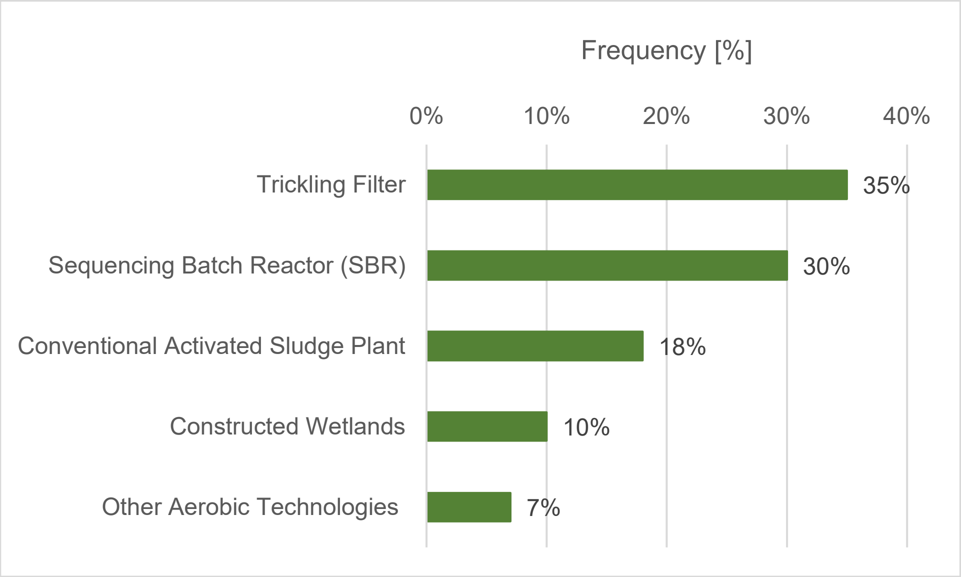

Figure 3: *The main technologies for secondary treatment in small-scale wastewater treatment plants in Switzerland. The data on their frequency was obtained from databases received from 17 cantons (see section 2.1.1), including a total of 3'207 systems with known technology. The category "Other Aerobic Technologies" comprises the rotating biological contactor (RBC), moving bed biofilm reactor (MBBR), fixed bed biofilm reactors, extended aeration, and membrane bioreactor (MBR).*

All the secondary treatment technologies are relevant for N_2O emissions, since partial nitrification is expected to take place in all of them. Only the constructed wetlands are considered relevant for CH_4 emissions in Table 4. This is because anaerobic conditions can occur, especially in HSSF wetlands, but also to a lesser extent in VSSF wetlands (from the digestion of accumulated solids and/or organic matter from plants) (Mander et al., 2014). For constructed wetlands, emission factors are documented accordingly (IPCC, 2014; Mander et al., 2014). For the other technologies listed under secondary treatment in Table 4, it is assumed that due to the aerobic operating conditions, negligible amounts of CH_4 are generated in the actual secondary treatment step. All CH_4 emissions are expected to take place in the primary treatment step (primary clarifier), especially because of the high retention time. This assumption, however, would benefit from a validation through sampling campaigns.

3.1.2 Quantities of wastewater collected in animal manure tanks and applied on land

In order to estimate the wastewater quantities applied on agricultural land (figure to be used for related emissions in agriculture), data was requested from the canton of Berne. Berne is considered to be fairly representative for Switzerland as it is the biggest canton covering both mountainous areas and low-lying agricultural zones. With 1’043’132 inhabitants by the end of 2020 (BFS, 2021), Berne has the second largest population (following the canton of Zurich).

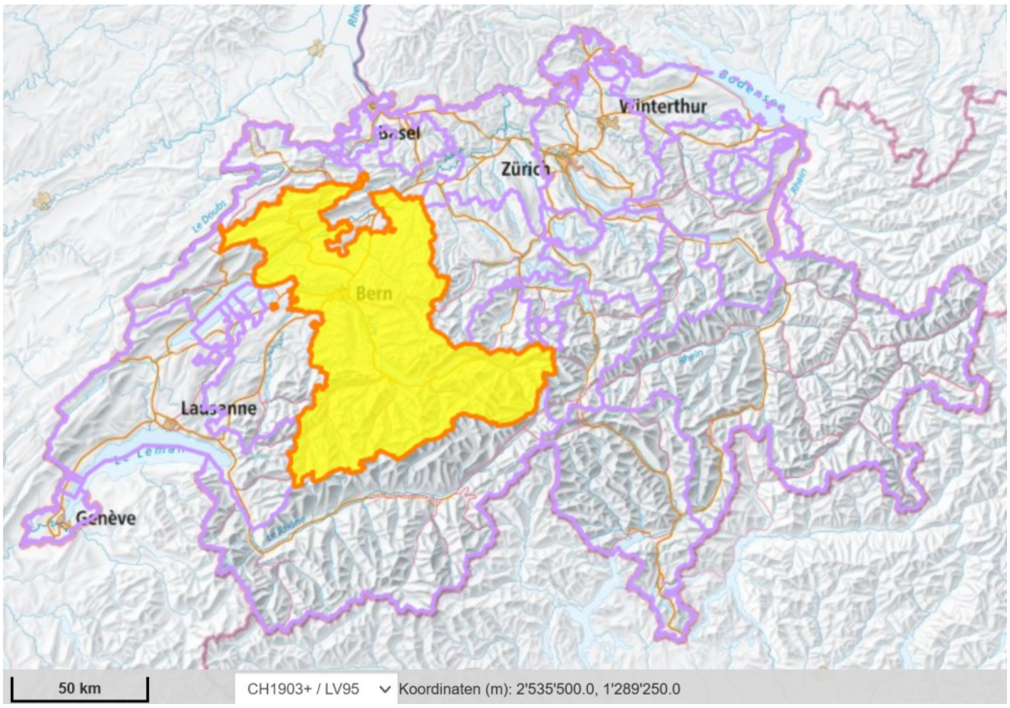

Figure 4: *Berne (highlighted in yellow) is the biggest Swiss canton covering both mountainous areas and low-lying agricultural areas (Source: map.geo.admin.ch). It is home to 20% of all farms in Switzerland.*

In Switzerland, a total number of 48’864 farms were registered in 2021, 9’977 (20%) of which in Berne (BFS, 2022). According to information from the authorities of the Canton of Berne, there were approximately 9’500 farms in 2022. About 50% of the 12’500 residential farm buildings (on average 8 rooms or PE each) are connected to public sewers, the other half are connected to manure tanks. Only an insignificant number is using small-scale treatment plants. In absolute numbers, approximately 50’000 PE capacity are connected to manure tanks in the Canton of Berne. It has to be assumed that today less than 8 residents live in a farm building on average. Assuming a 50% occupation, it is estimated that the wastewater of approx. 25’000 PE is going to manure tanks. Extrapolating this figure to the entire country, about **125’000 PE** would discharge their wastewater into manure tanks, corresponding to **1.44% of the Swiss population in 2021**.

This figure seems plausible: according to Berne’s database, all the 1’137 SSWWTPs in the canton have a total capacity to treat the wastewater of approx. 23’500 PE (this includes PE already counted under centralised systems, such as holiday houses and secondary residences). Since Berne is characterised particularly by mountain tourism, it is estimated that around 10’000 PE (actual utilisation) would be from permanent residents outside the centralised system. Applying the national average of 2.7% of the population with on-site systems to the Canton of Berne, this would correspond to 28’200 inhabitants not connected to public sewers. Given the figures on alternative connections above (25’000 PE manure tanks + 10’000 PE SSWWTPs), it has to be assumed that slightly more than 2.7% of the canton’s population are not connected to centralised systems (around 35’000 PE or 3.4%). This is possible, given that other, more urban and low-lying cantons (such as Basel and Geneva) have higher connection rates. Hence, this supports the estimates above.

The total number of farms in Switzerland has declined over the last decades (see Figure 5) and farms have generally increased in terms of area and number of animals per farm (BFS, 2022). It is not clear how this affects the number of farm buildings connected to manure tanks and even the number of people living in the corresponding buildings. In principle, a sewer connection or SSWWTP is required if there are no more cows or pigs allocated to a (former) farm building. Further inquiries with the cantonal authorities would be necessary.

In order to establish estimates for the period 1990-2021, a realistic assumption has to be made. Due to the dynamics of the last decades (including the increase of the sewer connection rate), it would not be suitable to assume a fixed population or percentage of the population connected to manure tanks for the entire period. Therefore, in a first approximation, a constant ratio between the share of population connected to manure tanks and the share of permanent residents connected to SSWWTPs is assumed. This results in plausible figures that are in general accordance with the data in Figure 5: according to the calculations, the number of manure tank connections amounted to 226’000 PE in 1996 (when still 6% of the Swiss population were not connected to centralised systems) and 125’000 PE in 2021 (2.7% not connected). This represents a 45% reduction. In the period from 1996[3] to 2021, the number of farms has decreased fairly linearly by about 40%.

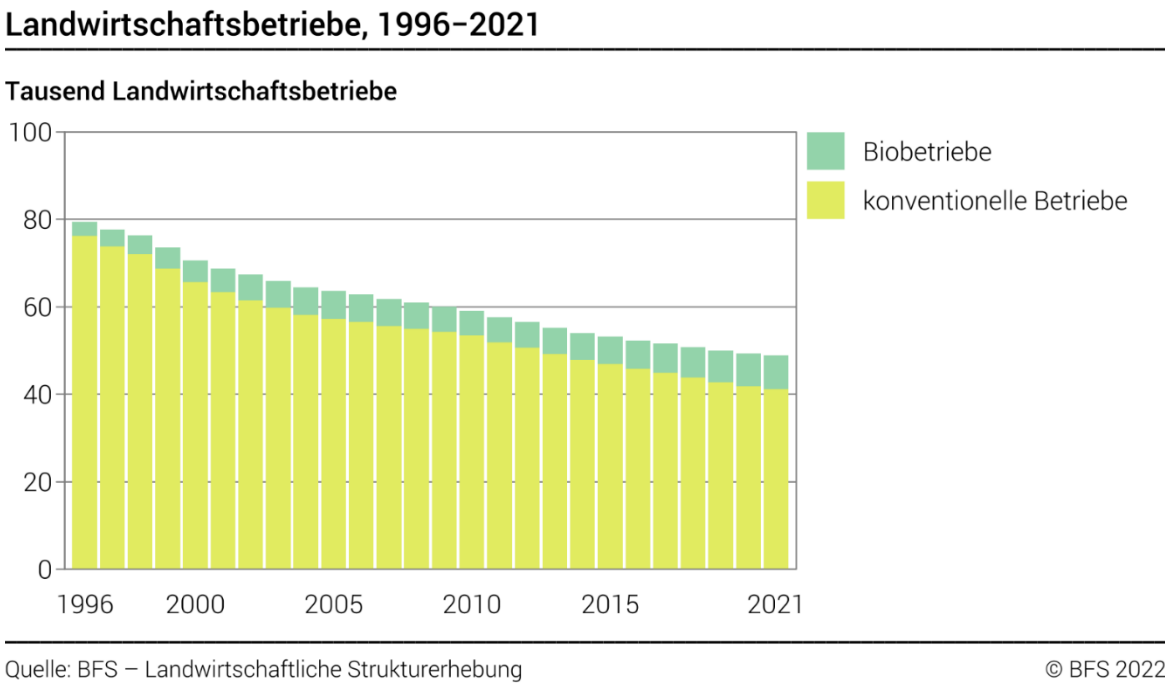

Figure 5: *Number of farms in Switzerland (in thousands) from 1996 to 2021 (yellow: conventional farms; green: organic farms)*

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[3] No data available before 1996.

3.1.3 Quantities of wastewater managed in on-site systems for the remaining population permanently without sewer access

If 2.7% of the Swiss population are not connected to public sewer systems (in 2021), with 1.44% connected to manure tanks, the remaining **1.26%** of the population (about **110’000 PE**) are served by on-site sanitation systems. The 1.26% do not include the population already accounted for under centralised wastewater management (i.e., owners/users of holiday houses/secondary residences, guests at hospitality services etc. who do have access to a sewer connection at their permanent residence, see section 2.2).

According to Table 4 (p. 24), the 1.26% are either served by **a) septic tanks** or by **b) SSWWTPs (combination primary clarifier + secondary treatment technology)**. Wastewater holding tanks are almost never used for residential buildings.

a) The cantonal authorities do not have up to date datasets on the number and size of anaerobic (septic) systems. Data are either unavailable or with the municipalities, with few exceptions. Examples with considerable numbers are Geneva (some 650 units), Vaud (some 1’200 – corresponding to 53% of all registered non-agricultural on-site systems), Valais (some several 10’000, with 3’000 alone in the Nendaz Municipality) and Ticino. The Canton of Berne, according to a representative, has only few. Since septic tanks are no longer considered state of the art treatment systems, the cantons no longer accept them as a permanent solution for new construction projects. Thus, it is impossible to quantify the number of septic tanks in Switzerland with an adequate precision. What is clear is that the septic tanks are being phased out for quite some time and can be considered as “legacy systems”. With the little information available, the authors assume here that some 30’000-50’000 septic systems may still exist in the country. The utilisation rate may, however, be low (< 50% of the design capacity averaged over the year). This is because – despite their large number – it can also be assumed that septic tanks are rarely installed at residential buildings with permanent occupation. They are most likely found in buildings that are presently used as holiday houses (e.g., in touristy areas like Nendaz), for hospitality services, alpine farms, hunting huts etc.

b) With the existing data from the cantonal authorities, it is difficult to quantify the number of permanent residents connected to a SSWWTP (in the data available from the cantons, no distinction is made between permanent residents, holiday houses, etc.). SSWWTPs are also installed at hospitality services, holiday cabins, etc., which are not to be counted within the 1.26%, to avoid double counts (see section 2.2). So even if the number of PE connected to SSWWTPs were known precisely, it would be difficult to state which fraction is from permanent residents. Moreover, the databases of most cantonal authorities either include data on the dimensioned capacity of SSWWTPs only, or no sizing data at all.

Due to these limitations, the 110’000 PE (or 1.26% of the Swiss population in 2021) from above are used for further consideration. With the assumption that septic tanks and holding tanks are hardly in use as standalone technologies for permanently occupied residential buildings, it can further be assumed that all 110’000 permanent residents living in non-networked areas are connected to SSWWTPs. It is also assumed that the overall technology mix as found in the data from the cantonal authorities (Figure 3 on p. 25) is applicable to the systems used by permanent residents in non-networked areas. Due to a lack of historical data, the technology mix is assumed to have remained constant over the entire period 1990-2021. As explained in the previous section, it would not be suitable to assume a fixed population or percentage of the population connected to SSWWTPs for the entire period. Therefore, the ratio of manure tank connections to SSWWTP connections is kept constant as a better approximation.

3.2 Sludge management from on-site sanitation systems in Switzerland

Regarding sludge management, information was requested from the authorities of the Canton of Berne. Berne is the canton with the largest number of recorded SSWWTPs (1137 out of 4024[4]). According to a representative, no quantification can be made of the number of systems or PE with an exceptional permission to discharge sludge outside centralised treatment systems. However, they are very few, and only where there is no accessibility by vehicle. This is very rare, especially for permanently occupied buildings.

It can be assumed for the entire country that only a negligible number of on-site sanitation systems (i.e., holding tanks, septic tanks or SSWWTPs) in very remote locations periodically discharge their sludge on pastures/grazing land (or dispose of dried sludge together with municipal solid waste), and that no quantitative data is currently available from other cantonal authorities. While there are these rare exceptions, it can be safely assumed that most of them concerns PE already accounted for under centralised treatment (such as holiday cabins or seasonally operated mountain huts). Thus, the authors confirm that it is valid to assume that all sludge of unconnected inhabitants which is not discharged on farm land after storage in manure tanks, is transported to the large-scale, centralised WWTPs. There, the sludge is typically fed into the sludge thickener / digester for treatment together with the primary and secondary sludge of the WWTP.

3.3 Estimation of GHG emissions from on-site sanitation systems in Switzerland

3.3.1 Temperature data

The temperature is relevant for both CH_4 and N_2O generation. CH_4 production can be expected above 12°C and N_2O above 5°C (see section 1.1.2), whereby large amounts of N_2O can be emitted particularly when the temperature sinks to a level where nitrification is inhibited and becomes unstable (Gruber, von Känel, et al., 2021), i.e., approximately in the range of 5-10°C or even below.

Water temperature data was available from 109 out of 126 documented SSWWTPs in the canton of Schwyz. The installations in Schwyz are located between 424 and 1’895 m a.s.l., with an average of 928 m and a median of 900 m. The temperature data is summarised in Table 5.

Table 5: *Water temperature data from small-scale wastewater treatment plants in the canton of Schwyz.*

	All data points (n=981)	**Winter months** (Nov-Feb, n=126)
Average of all water temperature data points [°C]	14.7	11.9
Minimum of all water temperature data points [°C]	4.0	4.0
Maximum of all water temperature data points [°C]	25.0	16.9
Percentage of data points > 5°C	99.6%	99.2%
Percentage of data points >10°C	89.8%	76.2%
Percentage of data points >12°C	77.9%	47.6%

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[4] Data was obtained from 17 out of 26 cantons. Due to their smaller population and area, the cantons without data available are expected to have considerably smaller numbers of SSWWTPs than Berne.

The data from Schwyz shows that CH_4 generation needs to be expected even during winter months (almost half the data points >12°C), even though the digestion processes are slowed considerably. As nitrification is still possible also during the winter time (average of water temperature data available at 11.9°C, more than three quarters of data points >10°C), it also has to be expected that some N_2O may be emitted even during the cold season. Throughout the year, the water temperature is almost always >10°C (90% of all data points), with an average of 14.7°C.

A similar situation can be expected in most cantons, as the average altitude of the SSWWTPs is similar or even lower (see Table 6).

Table 6: *Available data on the average altitude of the systems recorded by the cantons. Three figures are estimates by the authors (in italic).*

Canton	AG	AR	BL	FR	GE	GR	NW	SG	SO	SZ	TI	UR	VD	ZG	ZH
Average altitude [m a.s.l.]	482	865	*700*	777	420	*1000*	803	628	*800*	928	666	1267	859	848	690

No relevant soil and air temperature data could be found within the framework of this study.

3.3.2 Wastewater characteristics and treatment efficiencies in on-site systems

The following wastewater and treatment related activity data are used in the calculations (Annex 3):

- Country-specific per capita BOD_5: 60 mg BOD/person/day (IPCC, 2006)
- BOD removal in primary treatment: 30% (Tilley et al., 2014; VSA, 2017)
- Country-specific per capita nitrogen load in wastewater: annual (not constant) figures as proposed by Gruber, Joss, et al. (2021)
- Nitrogen removal in primary treatment: 5% (VSA, 2017)
- Nitrogen removal in secondary treatment: 25% as a weighted average of the various relevant treatment technologies (VSA, 2017). The 40% for primary and secondary treatment as per IPCC (2019) appear too high for small-scale systems with little process control.

3.3.3 Emission factors of SSWWTPs

According to sections 3.1.1 and 3.1.3, it is assumed that all the approx. 110’000 permanent residents living in non-networked areas are connected to SSWWTPs, using an anaerobic primary clarifier for primary treatment followed by a secondary treatment stage according to the identified technology mix (compare Figure 3 on p. 25):

- 35% trickling filters
- 30% sequencing batch reactors (SBR)
- 18% conventional activated sludge plants
- 10% constructed wetlands
- 7% other aerobic technologies

Emission factors (EF) for CH_4 and N_2O are thus required for both primary treatment and secondary treatment in these alternative systems.

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[5] For estimates applying COD instead of BOD, the conversion factor of 2 kg COD / kg BOD can be used, as suggested by Gruber, Joss, et al. (2021).

Emissions from **primary treatment** are assumed to be the same for all systems. Due to the high residence times in primary clarifiers used in SSWWTPs (especially the high solids retention time due to infrequent desludging, but also high hydraulic retention times), it is assumed that the **CH_4** EF of primary clarifiers is very similar to the one of septic tanks. According to the 2019 refinement to the IPCC Guidelines (Table 6.3 in IPCC, 2019), the EF proposed for septic tanks is 0.3 kg CH_4/kg BOD. While low temperatures during winter months and particularly in mountainous contexts can slow anaerobic digestion, the data from Schwyz shows that the assumption of a complete prevention of methanogenesis is incorrect (see section 3.3.1). Further, the so-called spring boil phenomenon (see section 1.2.1) can cause the delayed release of gases from sludge digestion once temperatures rise again. It is assumed that the IPCC EF includes these considerations. In accordance with section 1.1 of this report and Table 6.8A in IPCC (2019), it is further assumed that no **N_2O** is emitted from primary treatment (N_2O EF = 0).

Regarding secondary treatment, clear guidance on how to quantify the emission factor is available only for **constructed wetlands**, namely in a 2013 supplement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories (IPCC, 2014). For CH_4 as well as N_2O, a tier 1 method is proposed according to that reference (using default emission factors), because no country-specific measurements or emission factors are available as of now. Thus, for **CH_4** the proposed default values are B_0 = 0.6 kg CH_4/kg BOD (p. 6.13, IPCC, 2014), and a methane correction factor (MCF) of 0.1 for horizontal subsurface flow (HSSF) wetlands and 0.01 for vertical subsurface flow (VSSF) wetlands (Table 6.4 in IPCC, 2014). The resulting CH_4 EF (= B_0 * MCF) is 0.06 kg CH_4/kg BOD for HSSF wetlands and 0.006 kg CH_4/kg BOD for VSSF wetlands. It has to be noted here that IPCC (2014) does not speak about primary treatment and its effects on emissions at all. The same applies for the detailed review by Mander et al. (2014). Therefore, the authors of the present study conclude that separate consideration needs to be made for CH_4 emissions from primary treatment, as explained in the preceding paragraph. For **N_2O**, the default EF are 0.0079 kg N_2O-N/kg N for HSSF and 0.00023 kg N_2O-N/kg N for VSSF (Table 6.2 in IPCC, 2014). Since there is no data on the fraction of HSSF and VSSF wetlands existing in Switzerland, the authors recommend an assumption of a 50-50% apportionment (i.e., 5% and 5% for the 10% fraction “constructed wetlands”).

The **other secondary treatment technologies** (i.e., the remaining 90%) can all be characterised as aerobic technologies able to perform carbon removal and partial nitrification (see Table 4 in section 3.1.1). Therefore, similar EF can be assumed for all of these technologies, as a first estimate. For these technologies the EF are well described for conventional large-scale applications, specifically also for the context of Switzerland (Gruber, Joss, et al., 2021). As described in section 1.2.1, however, several differences need to be considered for application in SSWWTPs. Concerning **CH_4**, the authors argue that the emissions expected from these secondary treatment technologies are negligible, i) because they are aerobic processes, and ii) because CH_4 is released predominantly in the primary treatment tank with long retention times (see above). The latter appears to be in accordance with the figures for the CH_4 EF from septic tanks provided in Table 6.3 in IPCC (2019), where the EF with and without dispersal field are assumed to be the same (i.e., negligible emissions from the leach field itself). For **N_2O**, it has to be assumed that no stable nitrification can be ensured under the operating conditions of SSWWTPs (without much process control), and that denitrification rates are low (systems are not designed for it). Therefore, an EF of 0.08 kg N_2O-N/kg N is assumed, according to the lower left sector in Figure 1 (no stable nitrification, denitrification rate <40%) from Gruber et al. (2022). The need to assume high N_2O emissions from SSWWTPs is underlined by the findings of a study of SBR reactors for several Swiss mountain huts, where high levels of nitrite indicated an unstable, oxygen-deprived nitrification process (Vogt, 2020). The EF for N_2O emitted from nitrogen in the effluent of WWTPs (0.005 kg N_2O-N/kg N, assuming discharge to aquatic environments) is kept at the default value in the IPCC guideline (IPCC, 2006, 2019), due to limited data.

Table 7 provides an overview of the EF suggested for SSWWTPs in Switzerland.

Table 7: *Summary of emission factors (EF) suggested for small-scale wastewater treatment plants in Switzerland.*

	Primary treatment (in primary clarifier)	**Secondary treatment**		**Effluent**
	EF CH_4 [kg CH_4/kg BOD]	EF CH_4 [kg CH_4/kg BOD]	EF N_2O [kg N_2O-N/kg N]	EF N_2O [kg N_2O-N/kg N]
Horizontal subsurface flow (HSSF) constructed wetland	0.3	0.06	0.0079	0.005
Vertical subsurface flow (VSSF) constructed wetland	0.3	0.006	0.00023	0.005
Aerobic secondary treatment technologies (trickling filter, sequencing batch reactor (SBR), conventional activated sludge plant, other aerobic technologies)	0.3	0	0.08	0.005

3.3.4 Estimation of GHG emissions from permanent residents connected to on-site wastewater management systems

The CH_4 and N_2O emissions caused by permanent residents connected to on-site wastewater management systems (assuming all SSWWTPs, see section 3.1.3) are calculated for the period from 1990 to 2021 in Annex 3 based on the data and estimates. Figure 6 presents the findings in terms of actual emissions. In the year 2021 about 721 tons of CH_4 were emitted, and 65 tons of N_2O. These emissions have to be accounted for in the waste sector.

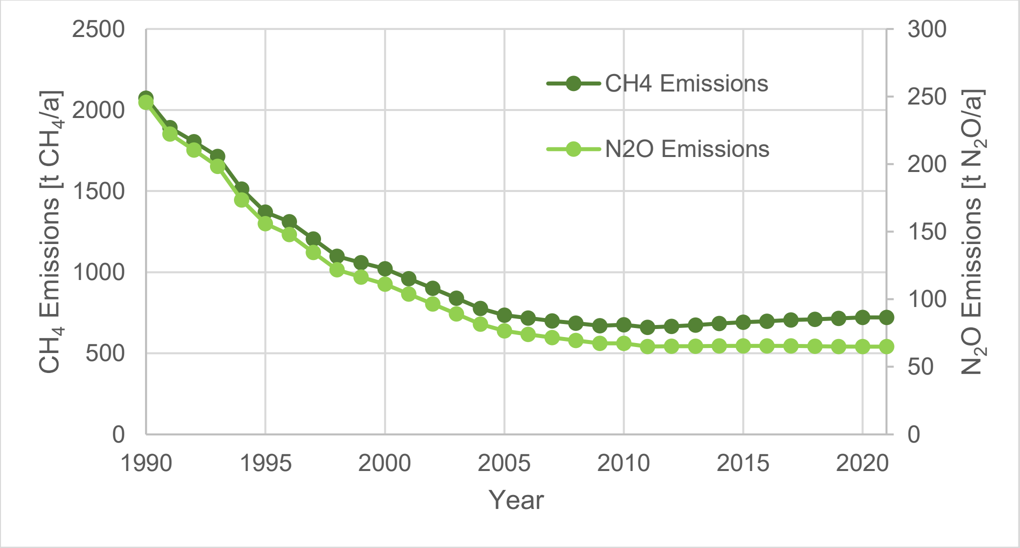

Figure 6: *Annual CH_4 and N_2O emissions from permanent residents connected to small-scale wastewater treatment plants, estimated for the period 1990-2021. These emissions are to be accounted for under the sector "waste". They do not include farms connected to manure tanks (emissions occurring in agriculture) and on-site sanitation users already considered under centralized wastewater management systems.*

The emissions were also converted into CO_2eq (Figure 7). The result shows that CH_4 and N_2O contribute approximately equal shares to the overall climate impact. In the year 2021 about 37'384 tons of CO_2eq were emitted by SSWWTPs used by permanent residents.

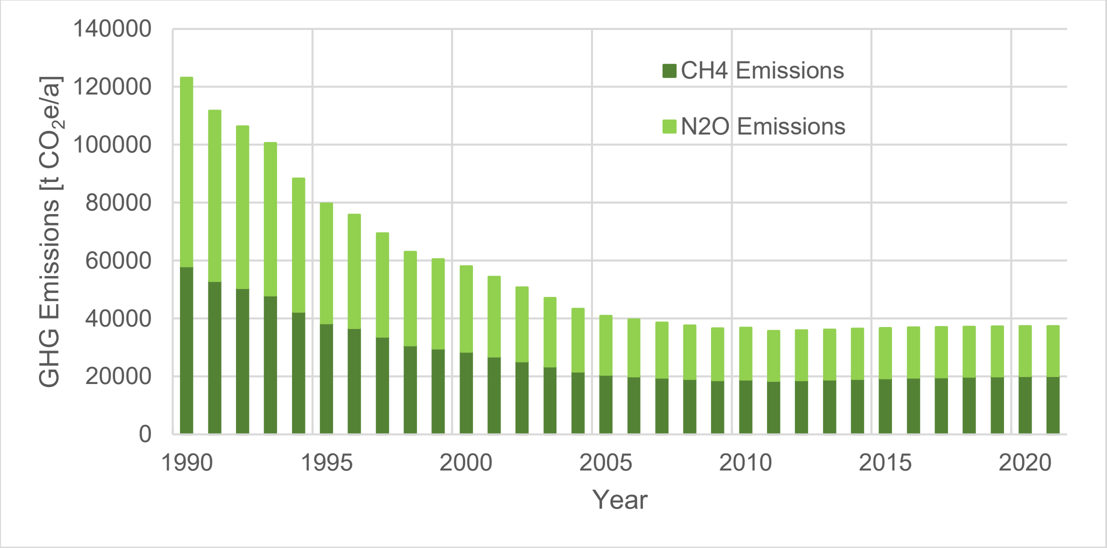

Figure 7: *Annual CH_4 and N_2O emissions in CO_2eq from permanent residents connected to small-scale wastewater treatment plants, estimated for the period 1990-2021. These emissions are to be accounted for under the sector "waste".*

3.3.5 Estimation of GHG emissions from non-permanent users of on-site sanitation (avoiding double counts and potential underestimates)

Besides the quantification of the connections to manure tanks (relevant for emissions in agriculture) and the connections of permanent residents to SSWWTPs, it is important to address the emissions of residents that are using on-site sanitation solutions only part-time (represented in grey colour in Figure 2 on p. 23). They include alpine farms, hospitality services, holiday houses and others. A precise quantification is impossible due to the inexistence of data such as number of visits, number of buildings per category and type of wastewater system used. To understand the order of magnitude of the related emissions, a calculation was made based on rough assumptions and estimates regarding the relevance and actual utilisation of various buildings that are used only part-time. The resulting assumptions and calculations are given in Table 8 and Table 9 below (further calculation details are given in Annex 3).

Table 8 presents the estimation of how many PE of wastewater are actually currently generated in the buildings that are used part-time or by a floating population and served by on-site sanitation systems. First, an estimate is made of the fraction of the year during which the buildings in each category are used on average (columns 2-3), and of the capacity utilisation (working load) of the sanitation system during the actual periods of use (column 4). Column 5 then estimates the percentage that each category contributes to the total installed on-site sanitation capacity in Switzerland. Here, the authors estimate that farms connected to manure tanks (see section 3.1.2 – emissions occurring in agriculture) contribute about 50% of the on-site sanitation capacity, and permanent residents (see sections 3.1.3 and 3.3.4) about 20%. Hence, the remaining 30% of all on-site sanitation systems would be in cases in which the users are already (partly) counted under centralised systems in terms of GHG emissions. Column 6 provides the number of PE derived from the percentages in column 5, departing from the figure of 250’000 PE manure tank capacity estimated in section 3.1.2 (which is estimated to represent 50% of the total on-site sanitation capacity in Switzerland). Column 7 then calculates the actual use (or wastewater generation) in PE using the percentages in columns 3 and 4. Finally, column 8 gives the estimated total number of PE that are already (partly) considered under centralised wastewater management in terms of their GHG emissions.

Table 8: *Rough estimation of the total number of population equivalents currently connected to on-site wastewater management systems but already counted under the centralised system.*

1	2	3	4	5	6	7	8
Category	**Description and typical use patterns**	**Estimated average fraction of year used**	**Estimated average capacity utilisation during occupied periods**	**Estimated percentage of total on-site sanitation capacity in Switzerland**	**Estimated total number of PE capacity**	**Estimated total number of PE actual use**	**Estimated total number of PE actual use and already considered under centralised**
Alpine farm (seasonally operated)	Seasonal use, 33-50% (summer months). Typical sanitation system: combined liquid manure (slurry) and wastewater tank, septic tank	40%	100%	10%	50’000	20’000 *(Assumption: 50% of their users are otherwise connected to manure tanks, 50% to centralised system.)*	10’000
Hospitality services in non-networked areas	Includes mountain huts, restaurants and lodges, camp grounds, sanatoria etc. with seasonal or year-round use, 33-100%. Typical sanitation system: SSWWTP	75%	60%	5%	25’000	11’250	11’250
Holiday houses / secondary residences in non-networked areas	Diverse use patterns, from occasional to seasonal to regular, 10-80% Typical sanitation system: holding tank, SSWWTP, septic tank	50%	80%	10%	50’000	20’000	20’000
Others	Hunting huts, dairy, sports facilities, motorway service areas, power stations, railway buildings, military infrastructure etc., 10-100% Typical sanitation system: SSWWTP, septic tank	100%	80%	5%	25’000	20’000	20’000
Subtotal				**30%**	**150’000**	**71’250**	**61’250**
Farms with 8 or more cattle or pigs				50%	250’000 (see section 3.1.2)		
Permanent residents				20%	100’000		

Today, about 60’000 PE of wastewater (i.e., the wastewater of about 0.7% of the Swiss population in 2021 connected to centralised systems) are estimated to be actually managed in on-site systems, by users that are residents connected to sewers most of the time. Thus, their GHG emissions are already (partly) accounted for – approx. 43 t CH_4 / a and 14 t N_2O / a in 2019[6] (see Table 9; as per the calculations by Gruber, Joss, et al., 2021). However, on-site sanitation systems have a higher emission factor (see sections 1.2.1 and 3.3.3). As there is no data on the technology mix of the on-site systems, it is assumed that 50% of the 60’000 PE wastewater are generated in septic tanks (or similar, without

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[6] 2019 is the last year for which emission data is available for centralised wastewater management (Gruber, Joss, et al., 2021). As an approximation, it is here assumed that the approx. 60’000 PE that are already considered under centralised remained constant during 2019-2021.

significant N_2O emissions but with the EF of septic tanks) and 50% in SSWWTPs (with EF as discussed in section 3.3.3). Accordingly, the actual emissions of these PE amount to an estimated 406 t CH_4 / a and 18 t N_2O / a for the year 2019 (see Table 9). Thus, only about 11% of the actual CH_4 emissions and 76% of the actual N_2O emissions of the systems used part-time or by a floating population are already accounted for under the centralised system; 363 t CH_4 / a and 4 t N_2O / a – or a total of about 11'315 t CO_2eq / a – should be added for completeness.

***Table 9:** Rough estimation of the actual CH_4 and N_2O emissions (in 2019) of the population equivalents connected to on-site wastewater management systems but already (partly) counted under the centralised system.*

Estimated emissions already considered under centralised (Gruber, Joss, et al., 2021)		**Estimated actual emissions of on-site systems with non-permanent users**		**Part of the emissions of on-site systems for which underestimation should be avoided**			
t CH_4 / a	t N_2O / a	t CH_4 / a	t N_2O / a	t CH_4 / a	t CO_2eq / a	t N_2O / a	t CO_2eq / a
43	14	406	18	363	10'153	4	1'162

These emissions are quite significant and need to be considered in the total emissions from wastewater management, together with those from centralised systems and those from permanent residents connected to SSWWTPs. However, the figures in Table 8 and Table 9 can only provide a very rough estimate of the order of magnitude of the current emissions (see section 3.4 on uncertainties). Concerning the entire period 1990-2021, it is even more difficult to make a quantification, and uncertainties increase. One could possibly assume that the number of PE actual use of on-site sanitation systems (i.e., the current 60'000 PE) remained in a constant ratio with the PE capacity of on-site sanitation systems for farms and permanent residents. However, it is not clear whether this would be a reasonable assumption. The authors refrain from extrapolating these emission estimates to the time series 1990-2021 as no data is available.

3.3.6 Estimation of total GHG emissions from on-site sanitation systems in Switzerland (excluding manure tank connections related to emissions occurring in agriculture)

As explained in the previous section, it is not possible to make a sound estimate of the GHG emissions from non-permanent users of on-site sanitation in Switzerland for the period 1990-2021. Thus, due to the unavailability of data for the entire period 1990-2021, the total GHG emissions from wastewater management including on-site sanitation were calculated for the year 2019 only, to get a rough idea of their order of magnitude. The calculations are shown in Table 10.

Table 10: *Estimation of the GHG emissions from wastewater management including on-site sanitation systems in Switzerland in 2019 (excluding emissions from manure tank connections occurring in agriculture). Emission estimates of the centralised system are given according to the proposed method by Gruber, Joss, et al. (2021).*

Methane (CH_4) emissions	t CH_4	t CO_2eq	%
Centralised wastewater management (Gruber, Joss, et al., 2021)	5’844	163’639	
Permanent residents with on-site sanitation (section 3.3.4)	715		10%
Non-permanent users of on-site sanitation (section 3.3.5)	406		6%
On-site sanitation (permanent + non-permanent; excluding manure tanks)	1’121	31’383	**16%**
Already considered under centralised (section 3.3.5)	-43		
Total wastewater management (centralised + on-site - already considered; excluding manure tanks)	6’922	193’821	100%
Nitrous oxide (N_2O) emissions	t N_2O	t CO_2eq	%
Centralised wastewater management (Gruber, Joss, et al., 2021)	1’918	508’229	
Permanent residents with on-site sanitation (section 3.3.4)	65		3%
Non-permanent users of on-site sanitation (section 3.3.5)	18		1%
On-site sanitation (permanent + non-permanent; excluding manure tanks)	83	22’155	**4%**
Already considered under centralised (section 3.3.5)	-14		
Total wastewater management (centralised + on-site - already considered; excluding manure tanks)	1’987	526’653	100%
All greenhouse gas emissions (CH_4 + N_2O)		t CO_2eq	%
Centralised wastewater management (Gruber, Joss, et al., 2021)		671’868	
On-site sanitation (permanent + non-permanent; excluding manure tanks)		53’538	**7%**
Total wastewater management (centralised + on-site - already considered; excluding manure tanks)		720’474	100%

The estimates indicate that in 2019 on-site wastewater management (excluding residents connected to manure tanks) contributed about 16% of the total CH_4 emissions from wastewater management (10% permanent residents, 6% non-permanent users), and 4% of the N_2O emissions (3% permanent residents, 1% non-permanent users). In terms of the overall GHG emissions from wastewater management (indicated in CO_2eq), on-site wastewater management was responsible for an estimated 7% of the total emissions. Considering the emissions from on-site sanitation (permanent residents + non-permanent users) in CO_2eq, CH_4 contributed 59% (31’383 t) and N_2O 41% (22’155 t) according to the estimates.

3.4 Uncertainties

The following table provides an estimate of the uncertainties of the activity data and emission factors used in this study. All estimates are based on expert judgements by the lead author, unless specified otherwise. Tables 2-1 and 2-2 in Kuenen & Dore (2019) were used for the expert judgements.

Table 11: *Uncertainty estimates for the activity data and emission factors.*

Parameter	**Description**	**Estimated uncertainty range**
Activity data		
Permanent population of Switzerland	• Official national statistics	1%
Percentage of population not connected to centralised wastewater management	• Official national statistics, based on periodic surveys with the cantons and extrapolations	1%
Population connected to manure tank / SSWWTP	• Number of farms well known, but not number of residents per farm building (capacity utilisation) • Extrapolations from Bern for Switzerland • No data on number of farms before 1996 • No data on number of permanent residents connected to on-site sanitation – estimation based on percentage not connected to sewerage and number of manure tank connections • Ratio manure tank to SSWWTP connections assumed constant	30%
Non-permanent users of on-site sanitation	• Very rough estimates by the authors, derived from assumptions only • Poor data on capacity utilisation of SSWWTPs	100%
On-site wastewater treatment technology mix used by permanent residents using SSWWTP	• Good data on shares of different treatment technologies from most relevant cantons • Assumed constant for 1990-2021	30%
On-site sanitation technology mix for non-permanent users of on-site sanitation	• No figures for number of septic tanks and context of use • No data available for different categories of users/owners of on-site systems (e.g., holiday houses vs permanent residence) • Assumed constant for 1990-2021	50%
Percentage of faecal sludge and sewage sludge being treated at centralised systems	• No data on number of exceptional permissions to discharge sludge outside centralised treatment systems, but reliable information that there are only very few.	5%
Country-specific per capita BOD	• From IPCC (2006)	30% (IPCC, 2019)
BOD removal in primary treatment	• From Tilley et al. (2014), VSA (2017)	30%
Country-specific per capita nitrogen load in wastewater	• From Gruber, Joss, et al. (2021)	10% (Gruber, Joss, et al., 2021)
Nitrogen removal in primary treatment	• From VSA (2017)	30%
Nitrogen removal in secondary treatment	• Technology specific • From VSA (2017)	50%
Emission factors		
CH_4 primary treatment (all technologies)	• From IPCC (2019)	40% (IPCC, 2019)
CH_4 secondary treatment HSSF constructed wetland	• From IPCC (2014)	61% (IPCC, 2014)
CH_4 secondary treatment VSSF constructed wetland	• From IPCC (2014)	86% (IPCC, 2014)
CH_4 secondary treatment aerobic	• EF assumed to be 0	100%
N_2O secondary treatment HSSF constructed wetland	• From IPCC (2014)	79% (IPCC, 2014)
N_2O secondary treatment VSSF constructed wetland	• From IPCC (2014)	70% (IPCC, 2014)
N_2O secondary treatment aerobic	• From Gruber et al. (2022)	100%
N_2O effluent all technologies	• From IPCC (2006, 2019)	100%

A more comprehensive uncertainty analysis was not possible within the framework of this study.

4 Discussion

The data compilation shows that little quantitative information exists on on-site wastewater management in Switzerland. This fact highlights the low overall significance of on-site sanitation, given that more than 97% of the population are served by centralised systems. The SSWWTP technology mix was established reliably. However, quantifying the number of inhabitants connected to these plants is extremely difficult. There is very little data available on septic tanks, holding tanks and their applications, even though these systems are still quite widespread in certain areas.

Whereas certain technologies are disappearing (e.g. septic tanks), others are increasing with time (e.g. SBR). Such dynamics are not only triggered by technological developments; they may also depend on economic developments, as the example of the changing number and size of farms shows, influencing the number of connections to manure tanks. Eventually, dynamics can also be initiated by political decisions – for instance if climate-friendly systems were promoted to reduce GHG emissions. For now, using the current technology mix for the entire time series since 1990 is the only option, because no data is available on the temporal evolution.

The temperature dependence of CH_4 and N_2O generation adds uncertainty to the EF. While the temperature data obtained in this study is not representative for the entire country, it shows that the previous assumption that no GHG are emitted from on-site sanitation systems in Switzerland is not correct, and that small systems need to be taken into consideration. In fact, it can be assumed that emissions of both CH_4 and N_2O from on-site systems occur throughout the entire year, although to a lesser extent in winter time.

In addition to the actual relevance of GHG emissions despite the cold climate, the present study highlights that both CH_4 and N_2O emissions can be very high from SSWWTPs – much higher than from well-controlled large-scale facilities. For sure, the differences between technologies are significant, comparing the example of the currently proposed N_2O EF of a VSSF constructed wetland and the other aerobic treatment systems such as SBR (0.02% vs 8%). However, the EF in this study is a very rough estimate and further consolidation through measurement campaigns would be helpful.

The increase in the connection rate to centralised wastewater management from 90% in 1990 to 97.3% in 2011 (assuming stagnation since then) led to a decrease in GHG emissions from on-site sanitation systems. Since 2011, however, the CH_4 emissions from permanent residents connected to SSWWTPs were found to slightly increase (see Figure 6). This is because the overall population in Switzerland continued to grow, while the connection rate to centralised treatment plants is currently assumed to remain constant. It is questionable whether this represents the reality, because the population growth predominantly takes place in areas connected to centralised systems, which would lead to an increase in the overall connection rate, and no increase in CH_4 emissions from SSWWTPs. The effect of an increase of emissions after 2011 is not visible for N_2O because the nitrogen load in wastewater has seen a constant decrease since 1990, compensating for the population growth.

Due to insufficient data, the authors refrain from calculating the emissions from non-permanent users of on-site sanitation systems (at holiday cabins, hospitality services etc.) for the entire time series from 1990 to 2021. Too many assumptions would have to be taken, leading to very high uncertainties and a questionable validity and significance of the calculated figures. Therefore, an estimate was made for 2019 only, which is the last year for which emission data from centralised wastewater management is available, and which is close to the current situation for which certain reasonable assumptions can be made. For the year 2019, this study estimates that, overall, on-site sanitation contributed 7% of the wastewater-related GHG emissions (in CO_2eq), even though 97.3% of the population were connected to centralised sewerage systems. CH_4, thereby is the most important GHG, contributing almost 60% of on-site sanitation's emissions (in CO_2eq) and an impressive 16% of the total CH_4 emissions from wastewater management. This might astonish, given the very high EF for N_2O of aerobic SSWWTPs and the global warming potential of N_2O being almost 10 times higher than that of CH_4. However, the importance of CH_4 becomes clear when considering that practically all of today's on-site sanitation systems include an anaerobic primary treatment stage with long residence times, leading to considerable methanogenesis.

Activity data for wastewater collected in animal manure tanks has been estimated in section 3.1.2. However, it is beyond the scope of this study to estimate emission factors and GHG emissions for this source.

In view of the high uncertainties indicated in section 3.4, it has to be kept in mind that the present study is a first desk-based quantification of Switzerland's GHG emissions from on-site sanitation, allowing to understand the orders of magnitude based on many assumptions and expert judgements. This study presents the best possible estimation that can currently be made using the limited data available.

5 Conclusion

This study presents a first, relatively rough estimate of CH_4 and N_2O emissions from on-site wastewater management in Switzerland. It highlights the importance of the related GHG emissions which have previously been neglected, given that more than 97% of the Swiss population are connected to centralised systems. The study shows that GHG emissions from on-site sanitation are not limited to the 2.7% of the population that don't have a sewer connection. On-site systems are more widespread – even parts of the population connected to sewers are using them, particularly for tourism. This study estimates that currently the wastewater of about 0.7% of the Swiss population with a sewer connection is actually managed in on-site systems. It is important to properly quantify the corresponding emissions to avoid double counts and underestimates.

Both gases are very important: CH_4 contributes an estimated 59% and N_2O 41% of on-site sanitation's GHG emissions in CO_2eq. It is therefore recommended to further examine the GHG emissions from small-scale wastewater treatment. Especially in the view of emerging novel technologies (e.g., vermifilters for aerobic primary treatment, urine-diversion) which will considerably reduce GHG emissions (e.g., by avoiding anaerobic digestion or unstable nitrification), policy making may direct on-site wastewater management in Switzerland towards a more climate-friendly approach. Although decentralised wastewater treatment (without considering farms connected to liquid manure tanks) provides a year-round sanitation solution to only approx. 1.3% of the Swiss population, on-site sanitation contributes more than 7% of the overall GHG emissions from wastewater treatment. Therefore, a wise technology selection may improve Switzerland's climate impact in the future.

The cantonal authorities may be able to provide additional relevant data. Future studies should therefore involve the cantonal authorities more closely. Further investigations are needed to reduce the uncertainties. Thereby, a focus should be on how to keep track of the temporal evolution of the technology mix for future GHG quantifications. For instance, it is important to know the number of inhabitants connected to manure tanks, which is a function of a relatively quick socio-economic development.

Emission data on small-scale systems of conventional aerobic wastewater treatment processes have been lacking for Switzerland. Measurement campaigns are needed to confirm whether the EF are actually as high as suspected, comparing multiple systems and operating conditions (including temperature regimes). Only detailed sampling data would help to establish the correlations between design, operation and emissions in order to produce more robust inputs for the GHG inventories (including the development of country-specific EF) and climate-friendly policy recommendations.

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Annex 1 Emission potentials for wastewater and sludge treatment / discharge systems

Table 12: *CH_4 and N_2O emission potentials for wastewater and sludge treatment and discharge systems according to the 2019 refinement to the 2006 IPCC guidelines for national GHG inventories* (IPCC, 2019).

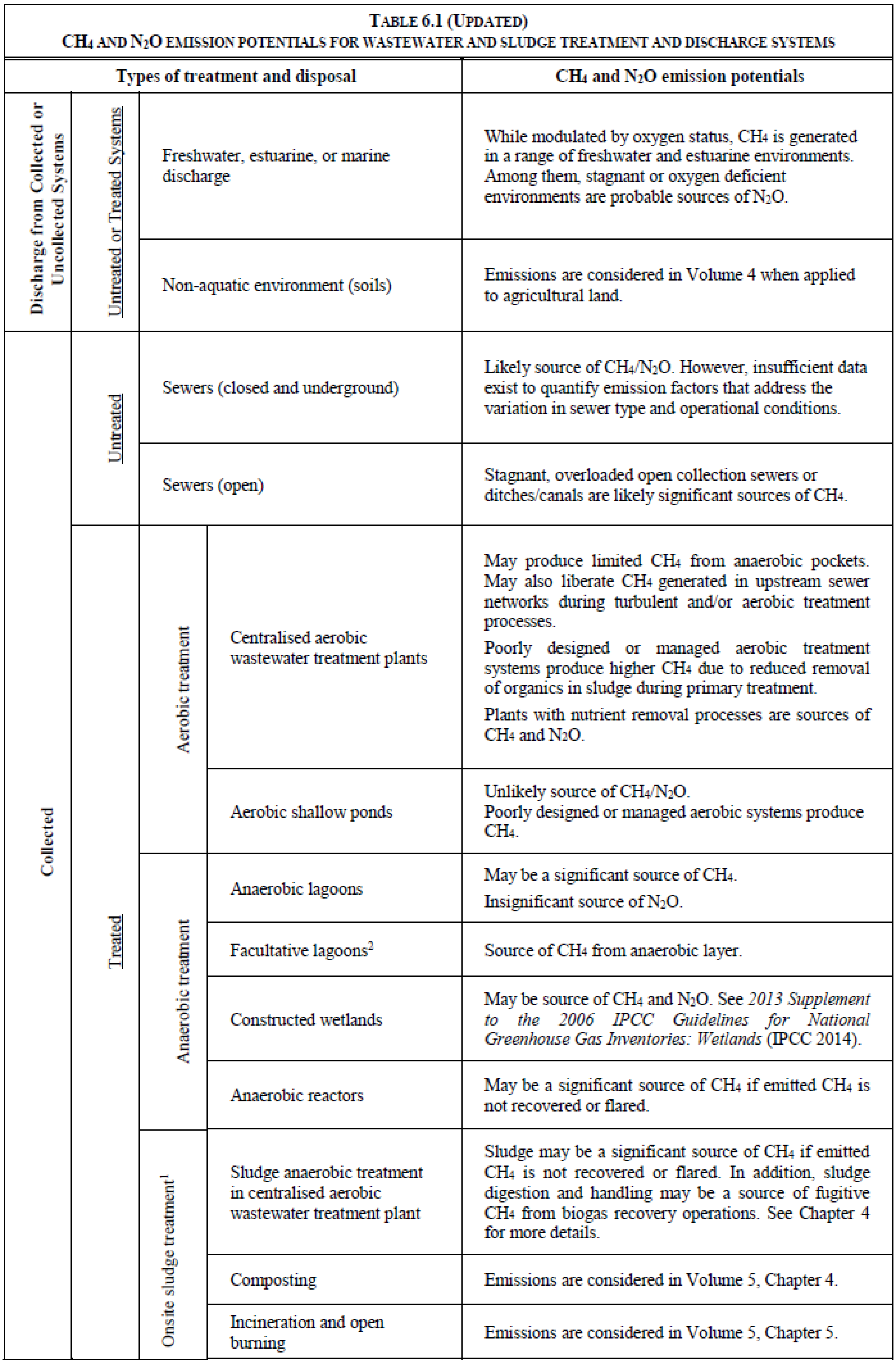

TABLE 6.1 (UPDATED)
CH_4 AND N_2O EMISSION POTENTIALS FOR WASTEWATER AND SLUDGE TREATMENT AND DISCHARGE SYSTEMS

Types of treatment and disposal				CH_4 and N_2O emission potentials
Discharge from Collected or Uncollected Systems	Untreated or Treated Systems	Freshwater, estuarine, or marine discharge		While modulated by oxygen status, CH_4 is generated in a range of freshwater and estuarine environments. Among them, stagnant or oxygen deficient environments are probable sources of N_2O.
		Non-aquatic environment (soils)		Emissions are considered in Volume 4 when applied to agricultural land.
Collected	Untreated	Sewers (closed and underground)		Likely source of CH_4/N_2O. However, insufficient data exist to quantify emission factors that address the variation in sewer type and operational conditions.
		Sewers (open)		Stagnant, overloaded open collection sewers or ditches/canals are likely significant sources of CH_4.
	Treated	Aerobic treatment	Centralised aerobic wastewater treatment plants	May produce limited CH_4 from anaerobic pockets. May also liberate CH_4 generated in upstream sewer networks during turbulent and/or aerobic treatment processes. Poorly designed or managed aerobic treatment systems produce higher CH_4 due to reduced removal of organics in sludge during primary treatment. Plants with nutrient removal processes are sources of CH_4 and N_2O.
			Aerobic shallow ponds	Unlikely source of CH_4/N_2O. Poorly designed or managed aerobic systems produce CH_4.
		Anaerobic treatment	Anaerobic lagoons	May be a significant source of CH_4. Insignificant source of N_2O.
			Facultative lagoons[2]	Source of CH_4 from anaerobic layer.
			Constructed wetlands	May be source of CH_4 and N_2O. See *2013 Supplement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories: Wetlands* (IPCC 2014).
			Anaerobic reactors	May be a significant source of CH_4 if emitted CH_4 is not recovered or flared.
		Onsite sludge treatment[1]	Sludge anaerobic treatment in centralised aerobic wastewater treatment plant	Sludge may be a significant source of CH_4 if emitted CH_4 is not recovered or flared. In addition, sludge digestion and handling may be a source of fugitive CH_4 from biogas recovery operations. See Chapter 4 for more details.
			Composting	Emissions are considered in Volume 5, Chapter 4.
			Incineration and open burning	Emissions are considered in Volume 5, Chapter 5.

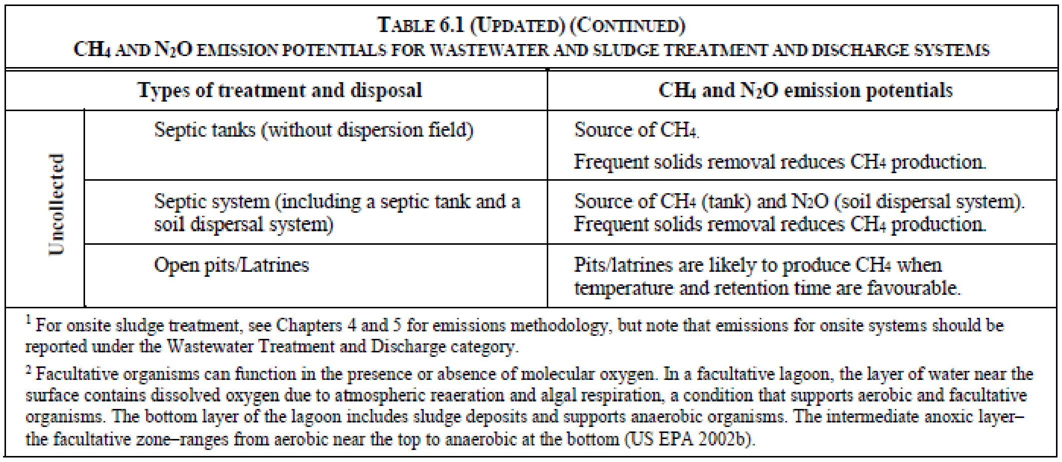

TABLE 6.1 (UPDATED) (CONTINUED)
CH_4 AND N_2O EMISSION POTENTIALS FOR WASTEWATER AND SLUDGE TREATMENT AND DISCHARGE SYSTEMS

	Types of treatment and disposal	CH_4 and N_2O emission potentials
Uncollected	Septic tanks (without dispersion field)	Source of CH_4. Frequent solids removal reduces CH_4 production.
	Septic system (including a septic tank and a soil dispersal system)	Source of CH_4 (tank) and N_2O (soil dispersal system). Frequent solids removal reduces CH_4 production.
	Open pits/Latrines	Pits/latrines are likely to produce CH_4 when temperature and retention time are favourable.

[1] For onsite sludge treatment, see Chapters 4 and 5 for emissions methodology, but note that emissions for onsite systems should be reported under the Wastewater Treatment and Discharge category.

[2] Facultative organisms can function in the presence or absence of molecular oxygen. In a facultative lagoon, the layer of water near the surface contains dissolved oxygen due to atmospheric reaeration and algal respiration, a condition that supports aerobic and facultative organisms. The bottom layer of the lagoon includes sludge deposits and supports anaerobic organisms. The intermediate anoxic layer–the facultative zone–ranges from aerobic near the top to anaerobic at the bottom (US EPA 2002b).

Annex 2 Wastewater treatment and discharge pathways according to IPCC (2019)

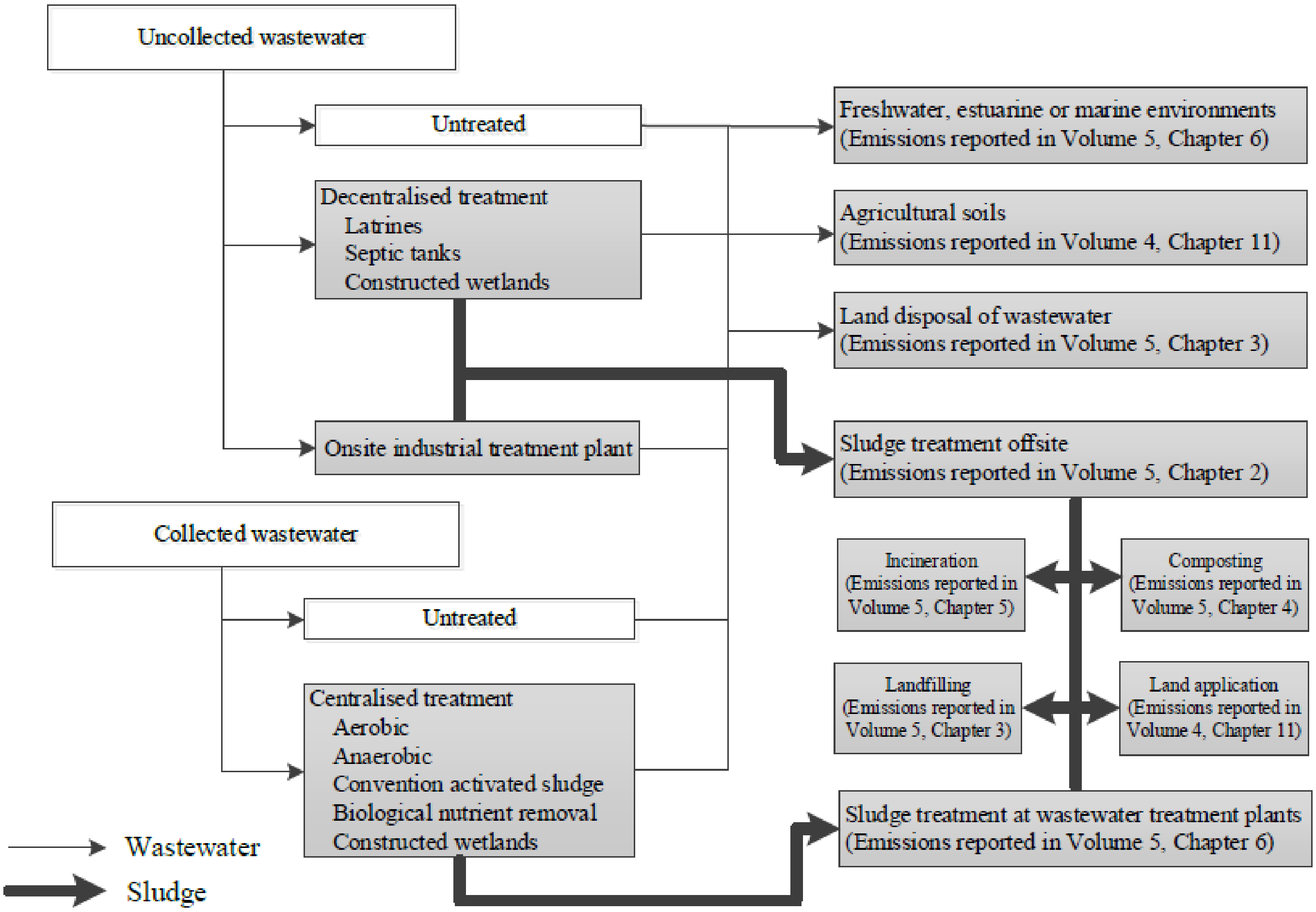

Figure 8: *Wastewater treatment and discharge pathways as per the 2019 refinement to the 2006 IPCC guidelines for national GHG inventories. Source:* IPCC (2019)

Annex 3 Calculations

All data and calculations used in this report can be found in the appendant Excel file.