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Losses of plant protection products via drainages in Switzerland – conceptual model and mitigation measures

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Summary

In Switzerland, approximately 20% of the utilized agricultural area is drained to ameliorate its production capacity. This report evaluates the extent to which these systems may cause Plant Protection Product (PPP) losses. In the first part we discuss transport processes of PPPs to agricultural drains, including fate processes of PPPs, impact of soil and surface hydrology, as well as interactions between hydrological flow paths and PPP properties. Then we describe existing physical and computational models, the registration model EXPOSIT, and existing decision trees to assess the potential for preferential flow. Based on an extensive literature review, including data from Swiss experiments, a conceptual model and flow diagram is presented, which shows the interactions between the most important processes and parameters impacting PPP losses through tile drainage. Finally, we evaluate mitigation measures against PPP losses to drainages.

Transport of plant protection products to agricultural drains

- The many PPPs on the market exhibit very different properties. The dissipation half-life (DT_{50}) is very variable and can depend on soil texture, organic matter, bacterial communities, water content, and temperature. Adsorption strength (K_{oc}) is very variable between substances.
- Soils conduct water in a non-uniform manner. Preferential flow is rather the rule than the exception and has a strong impact on PPP losses through drainage. Preferential flow transports solutes very quickly to drains. Therefore, contact time between soil surfaces and PPPs is strongly reduced with preferential flow through macropores.
- Consequently, PPP adsorption strength has a much weaker impact on peak losses via drainage than it would have with slower transport through the soil matrix. On the other hand, DT_{50} can have an impact on peak PPP losses in combination with the time between PPP application and the next intense rain event.
- Macropores can be biopores or shrinkage cracks. Macropores are most stable in loamy and clayey soils. Biopores are temporally more stable than shrinkage cracks as they do not retract upon rewetting. Biopores are most abundant in loamy soils. In Switzerland, most soils are prone to preferential flow via cracks or biopores. In Switzerland sandy or clayey soils are not very abundant.
- Hydrological behavior of drains is affected by the local groundwater table, or seasonally perched water table in the presence of a clay-confining layer.
- The general hydrological behavior of the drain will have a strong impact on PPP losses at the plot scale, and will influence the partition between leaching losses, drainage losses and surface runoff/erosion losses.
- The effect of antecedent soil moisture on preferential flow depends on soil texture and cannot be generalized. It also depends on the general hydrogeological behavior of the plot or catchment.
- Individual processes leading to PPP losses via drainage are relatively well understood, but the various interactions between processes in heterogeneous soil and farm contexts such as drainage design, crops, tillage practices, and PPP use make it difficult to disentangle the quantitative relevance of each parameter.
- PPP losses via drainage are important with regard to concentrations and load. They are on average smaller than losses via runoff and erosion but higher than losses via leaching.

Decision trees and conceptual model

- We listed key parameters influencing drainage losses and assessed their impact and uncertainty. The relationships between those parameters were shown as a flow diagram.
- Many relationships are multi-parameter and non-linear. Several variables have uncertain impacts on drainage losses. The clearest parameters are singled out as focus points for mitigation measures.
- High soil organic carbon content tends to increase saturated hydraulic conductivity but also to decrease preferential flow. Adsorption tends to increase, so total PPP losses decrease.
- The time between PPP application and the first intense rain event is the most important parameter controlling drainage peak losses. If the first rain event is weak, peak losses may be substantially reduced but not necessarily seasonal losses.
- Many decision trees have been suggested to quantify the extent of macropore flow in soils. In Switzerland, loamy soils are dominant. Swiss soils often fall in the medium risk category according to those decision trees.
- The comparison of rare suitable experimental data against predictions by the regulatory model EXPOSIT suggests that this model might not be sufficiently robust to allow for a realistic worst-case risk evaluation of PPP use on drained agricultural land. However, data availability is too limited to draw reliable and general conclusions for Switzerland.

Typical mitigation measures against PPP losses to drainage

- The TOPPS working group suggested various mitigation measures and ranked them in relation to the risk of losses defined in the decision tree. Most mitigation measures for the low risk level are already part of the Proof of Ecological Performance in Switzerland. An assessment of the potential of each mitigation measure for Switzerland is summarized in a table.
- Most mitigation measures against leaching losses will also reduce drainage losses.
- Mitigation measures recommended against runoff and erosion losses are mainly positive against losses via drainage.
- However, some measures against runoff/erosion such as no-till can have both positive and negative impacts on drainage losses. By precaution, no-till should not necessarily be promoted on plots that are flat and prone to be drained.
- Based on the conceptual model and the literature, optimizing the date of application is the measure with the highest mitigation potential. In practice, the scope is however limited.
- Some technical mitigation measures such as constructed wetlands and controlled drainage are quite effective but application not realistic in Switzerland. Changes in land uses could be an avenue, such as paludiculture for energy crops, wetland agroforestry, rice cultivation. However, these options are either niche crops or less profitable, for now, than existing use as drained arable land.
- Therefore, drainage-specific measures are rare and not applicable at a large scale.
- The lack of specific measures and precise maps of drained areas make regulation of the use of PPPs on drained land with site-specific measures unrealistic. This is in contrast, to the already enforced regulation by the PPP registration process for runoff and drift.

Zusammenfassung

In der Schweiz werden etwa 20 % der Landwirtschaftsfläche drainiert, um die Produktivität zu verbessern. In diesem Bericht wird evaluiert, in welchem Ausmass solche Entwässerungssysteme Verluste von Pflanzenschutzmitteln (PSM) verursachen können. Im ersten Teil diskutieren wir die Transportprozesse von PSM zu den landwirtschaftlichen Drainagen, einschliesslich der Prozesse, die das Verhalten von PSM bestimmen, der Auswirkungen der Boden- und Oberflächenhydrologie sowie der Beziehungen zwischen den Fliesswegen und den Eigenschaften von PSM. Dann beschreiben wir verfügbare physikalische Modelle und Computersimulationen, das Expositionsmodell EXPOSIT und bestehende Entscheidungsbäume, mit denen präferenzielle Fliesswege abgeschätzt werden. Auf der Grundlage einer umfangreichen Literaturrecherche, einschliesslich Daten aus Schweizer Versuchen, werden ein konzeptionelles Modell und ein Flussdiagramm vorgestellt, die die Wechselwirkungen zwischen den wichtigsten Prozessen und Parametern zeigen, die sich auf die PSM-Verluste über Drainagesysteme auswirken. Schliesslich evaluieren wir Massnahmen zur Verminderung von PSM-Verlusten über Drainagen.

Transport von Pflanzenschutzmitteln in landwirtschaftliche Drainagesysteme

- Es sind zahlreiche PSM auf dem Markt, die sehr unterschiedliche Eigenschaften aufweisen. Der DT_{50}-Wert (Halbwertszeit der PSM-Konzentration) ist sehr variabel und kann von der Bodenbeschaffenheit, der organischen Substanz, der Bakterienflora, dem Wassergehalt und der Temperatur abhängen. Auch der Adsorptionskoeffizient (K_{oc}) ist je nach Substanz sehr unterschiedlich.
- Böden leiten das Wasser in ungleichmässiger Weise. Präferenzielle Fliesswege sind eher die Regel als die Ausnahme und haben einen bedeutenden Einfluss auf PSM-Verluste durch Drainagen. Durch präferenzielle Fliesswege werden gelöste Stoffe sehr schnell zu den Drainageleitungen transportiert. Aus diesem Grund wird die Kontaktzeit zwischen Bodenoberfläche und PSM mit präferenziellen Fliesswegen über Makroporen stark reduziert.
- Folglich hat die Stärke der Adsorption von PSM einen viel schwächeren Einfluss auf die Spitzenverluste über Drainagen, als dies bei einem langsameren Transport durch die Bodenmatrix der Fall wäre. Dagegen kann der DT_{50}-Wert einen wesentlichen Einfluss auf die PSM-Spitzenverluste haben, je nach der Zeitdauer zwischen der PSM-Applikation und dem nächsten intensiven Regen.
- Makroporen können Bioporen oder Trockenrisse sein. Makroporen bilden sich vor allem in lehmigen und tonigen Böden. Bioporen sind zeitlich stabiler als Trockenrisse, da sie sich bei erneuter Befeuchtung nicht schliessen. Bioporen sind am häufigsten in lehmigen Böden vorhanden. In der Schweiz sind die meisten Böden anfällig für präferenzielle Fliesswege über Risse oder Bioporen. Es gibt nur wenige sandige oder tonige Böden.
- Das hydrologische Verhalten der Drainagen wird beeinflusst durch den lokalen Grundwasserspiegel oder durch einen jahreszeitlich bedingten erhöhten Wasserspiegel, wenn eine Tonschicht vorhanden ist.
- Das allgemeine hydrologische Verhalten der Drainage hat einen bedeutenden Einfluss auf die PSM-Verluste auf der Ebene der Parzelle und auf die Aufteilung der Verluste über Auswaschung, Drainageabfluss und oberflächliche Abschwemmung/Erosion.
- Der Einfluss der vorangehenden Bodenfeuchtigkeit auf die präferenziellen Fliesswege hängt von der Bodenbeschaffenheit ab und kann nicht allgemein beschrieben werden. Das allgemeine hydrogeologische Verhalten der Parzelle oder des Einzugsgebiets haben ebenfalls relevante Auswirkungen.

- Während einzelne Prozesse, die zu PSM-Verlusten über das Drainagesystem führen, relativ gut verstanden werden, erschweren es die vielfältigen Wechselwirkungen zwischen den Prozessen in heterogenen Böden und Parametern, welche durch die Landwirtschaftsbetriebe bestimmt werden (wie z. B. das Design des Drainagesystems, die angebauten Kulturen, Bodenbearbeitungspraktiken und der PSM-Einsatz), den quantitativen Einfluss der einzelnen Parameter zu ermitteln.
- Die PSM-Verluste über das Drainagesystem haben einen bedeutenden Einfluss auf die PSM-Konzentrationen und Frachten. Sie sind im Durchschnitt geringer als die Verluste über oberflächliche Abschwemmung (Runoff) und Erosion, aber höher als Verluste durch Auswaschung.

Entscheidungsbäume und konzeptionelles Modell

- Wir haben eine Liste mit den Schlüsselparametern zusammengestellt, die einen Einfluss auf die Verluste über das Drainagesystem haben und deren Auswirkungen und Unsicherheiten bestimmt. Die Beziehungen zwischen diesen Parametern wurden in einem Flussdiagramm dargestellt.
- Viele Beziehungen haben viele Parameter und sind nichtlinear. Bei verschiedenen Variablen sind die Auswirkungen auf die Verluste über das Drainagesystem unsicher. Für Massnahmen zur Reduktion von PSM-Verlusten wird der Fokus auf die Parameter mit dem klarsten Einfluss gelegt.
- Ein hoher Gehalt an organischem Kohlenstoff im Boden erhöht tendenziell die gesättigte hydraulische Leitfähigkeit, verringert aber auch den Verlust über präferenzielle Fliesswege. Die Adsorption nimmt tendenziell zu, womit die PSM-Verluste insgesamt sinken.
- Die Zeit zwischen der PSM-Anwendung und dem ersten starken Regen ist der Parameter mit dem grössten Einfluss auf die Spitzen der PSM-Verluste über Drainagenabfluss. Wenn das erste Regenereignis schwach ist, können die Verlustspitzen erheblich abgeschwächt werden, aber nicht zwingend die saisonalen Verluste.
- Es wurden verschiedene Entscheidungsbäume vorgeschlagen, um das Ausmass von Makroporenfluss in Böden zu quantifizieren. In der Schweiz sind die meisten Böden lehmig. Die Schweizer Böden fallen nach diesen Entscheidungsbäumen oft in die mittlere Risiko-Kategorie.
- Ein Vergleich der beschränkt verfügbaren Versuchsdaten mit Vorhersagen des EXPOSIT-Modells zeigt, dass dieses Modell möglicherweise nicht konservativ genug ist, um eine realistische Risikobewertung eines Worst-Case-Szenarios des PSM-Einsatzes auf drainierten landwirtschaftlichen Flächen zu ermöglichen. Die Verfügbarkeit geeigneter Daten ist jedoch zu begrenzt, um zuverlässige und allgemeine Schlussfolgerungen für die Schweiz zu ziehen.

Typische Massnahmen zur Verminderung von PSM-Verlusten über das Drainagesystem

- Die TOPPS-Arbeitsgruppe schlug verschiedene Massnahmen zur Verminderung der Verluste vor und wies ihnen bezogen auf das Verlustrisiko gemäss Entscheidungsbaum einen Rang zu. Die meisten Massnahmen mit niedrigen Risikoniveaus sind bereits Teil des Ökologischen Leistungsnachweises in der Schweiz. Eine Einschätzung des Potenzials der einzelnen Massnahmen zur Reduktion des PSM-Verlustes für die Schweiz ist in einer Tabelle zusammengefasst.
- Die meisten Massnahmen zur Eindämmung der Verluste durch Auswaschung verringern auch die Verluste über das Drainagesystem.
- Die empfohlenen Massnahmen zur Reduktion der Verluste über oberflächliche Abschwemmung und Erosion wirken sich überwiegend positiv auf die Verluste über das Drainagesystem aus.
- Einige Massnahmen gegen Runoff/Erosion, wie z. B. die Direktsaat, können aber sowohl positive als auch negative Auswirkungen auf die Verluste über das Drainagesystem haben. Vorsichtshalber sollte die Direktsaat nicht unbedingt auf Parzellen erfolgen, die flach sind und eher entwässert werden müssen.

- Das konzeptionelle Modell und Daten aus der Literatur zeigen, dass ein optimaler Zeitpunkt der PSM-Anwendung die Massnahme mit dem höchsten Potenzial zur Reduktion des PSM-Verlusts ist. In der Praxis ist das Zeitfenster für eine mögliche Anwendung jedoch begrenzt.
- Einige technische Massnahmen wie z. B. Pflanzenkläranlagen oder eine kontrollierte Drainage sind recht wirksam, aber in der Schweiz ist die breitere Anwendung kaum realistisch. Auch eine andere Landnutzung könnte ein Weg sein, z. B. die Paludikultur mit Energiepflanzen, die Agroforstwirtschaft in Feuchtgebieten oder der Reisanbau. Diese Optionen sind jedoch entweder Nischenkulturen oder momentan noch weniger rentabel als die derzeitige Nutzung als drainiertes Ackerland.
- Aus diesem Grund stehen nur sehr begrenzt spezifische Massnahmen für drainierte Parzellen zur Verfügung und sie sind nicht in grossem Massstab anwendbar.
- Das Fehlen spezifischer Massnahmen und präziser Karten der drainierten Gebiete macht es schwierig, den PSM-Einsatz auf drainierten Parzellen an standortspezifische Massnahmen regulatorisch zu binden, im Gegensatz dazu, was bei Zulassungsverfahren von PSM bezüglich Runoff und Abdrift bereits durchgesetzt wird.

Résumé

En Suisse, environ 20 % de la surface agricole utile a été drainée pour améliorer sa capacité de production. Le présent rapport évalue dans quelle mesure les systèmes de drainage peuvent causer des pertes de produits phytosanitaires (PPh). Dans la première partie, nous examinons les modes d'écoulement des PPh vers les drains agricoles, y compris les processus de dégradation des PPh, l'impact de l'hydrologie du sol et de surface, ainsi que les interactions entre les mécanismes d'écoulement hydrologiques et les propriétés des PPh. Ensuite, nous décrivons les modèles physiques et informatiques existants, le modèle de régulation EXPOSIT et les arbres de décision à disposition pour évaluer le potentiel d'écoulement préférentiel. Sur la base d'un examen approfondi de la littérature, y compris des données provenant d'expériences suisses, un modèle conceptuel et un diagramme des flux sont présentés. Ceux-ci montrent les interactions entre les processus et les paramètres les plus importants ayant un impact sur les pertes de PPh par les systèmes de drainage souterrains. Enfin, nous évaluons les mesures visant à atténuer les pertes de PPh dues aux drainages.

Transfert de produits phytosanitaires vers les drains agricoles

- Les nombreux PPh disponibles sur le marché présentent des propriétés très différentes. La demi-vie de dissipation (DT_{50}) est très variable et peut dépendre de la texture du sol, de la matière organique, des communautés bactériennes, de la teneur en eau et de la température. La force d'adsorption (K_{oc}) est très variable selon les substances.
- Les sols conduisent l'eau de manière non uniforme. L'écoulement préférentiel est plutôt la règle que l'exception et a un fort impact sur les pertes de PPh par drainage. L'écoulement préférentiel amène très rapidement les solutés aux drains. Par conséquent, le temps de contact entre la surface des sols et les PPh est très réduit du fait de l'écoulement préférentiel à travers les macropores.
- C'est pourquoi la force d'adsorption des PPh a un impact beaucoup plus faible sur les principales pertes par les systèmes de drainage qu'elle ne l'aurait avec un transport plus lent à travers la matrice du sol. D'un autre côté, le DT_{50} peut avoir un impact sur les pertes maximales de PPh en combinaison avec le temps écoulé entre l'application du PPh et le prochain épisode de pluie intense.
- Les macropores peuvent être des biopores ou des craquelures de séchage. Les macropores se forment surtout dans les sols limoneux et argileux. Les biopores sont plus stables dans le temps que les craquelures de séchage car elles ne se rétractent pas en cas de réhumidification. Les biopores sont plus abondantes dans les sols limoneux. En Suisse, la plupart des sols favorisent l'écoulement préférentiel par les craquelures ou les biopores. Il y a peu de sols sableux ou limoneux.
- Le comportement hydrologique des drains est affecté par la nappe phréatique locale, ou par des nappes perchées saisonnières en présence d'une couche d'argile imperméable.
- Le comportement hydrologique général du système de drainage aura un fort impact sur les pertes de PPh à l'échelle de la parcelle, et influencera la répartition entre les pertes par lixiviation, les pertes par drainage et les pertes par ruissellement de surface ou érosion
- L'effet de la teneur en humidité antérieure du sol sur l'écoulement préférentiel dépend de la texture du sol et ne peut être généralisé. Il dépend également du comportement hydrogéologique général de la parcelle ou du bassin versant.
- Les processus individuels conduisant à des pertes de PPh par drainage sont relativement bien compris, mais les diverses interactions entre les processus dans des contextes de sols et d'exploitations agricoles hétérogènes, tels que la conception des systèmes de drainage, les cultures, les techniques de travail du sol et l'utilisation de PPh, rendent difficile de distinguer l'importance quantitative de chaque paramètre.

- Les pertes de PPh par les systèmes de drainage sont importantes à la fois en concentration et en charge totale. Elles sont en moyenne inférieures aux pertes dues au ruissellement et à l'érosion, mais supérieures aux pertes dues au lessivage.

Arbres de décision et modèles conceptuels

- Nous avons dressé la liste des principaux paramètres influençant les pertes par drainage et évalué leur impact et leur incertitude. Nous avons ensuite présenté les relations entre ces paramètres sous forme d'un diagramme de flux.
- De nombreuses relations sont multiparamétriques et non linéaires. Plusieurs variables ont un impact incertain sur les pertes par drainage. Les paramètres les plus clairs sont identifiés comme des cibles pour les mesures d'atténuation.
- Une teneur élevée en carbone organique dans le sol tend à augmenter la conductivité hydraulique à saturation, mais aussi à diminuer l'écoulement préférentiel. L'adsorption a tendance à augmenter, d'où une diminution des pertes totales de PPh.
- Le temps entre l'application des PPh et la première forte pluie est le paramètre le plus important pour contrôler les pertes maximales par drainage. Si le premier épisode de pluie est faible, les pertes maximales peuvent être considérablement réduites, mais pas nécessairement les pertes saisonnières.
- De nombreux arbres de décision ont été proposés pour quantifier l'étendue de l'écoulement via les macropores dans le sol. En Suisse, les sols sont principalement limoneux. Selon ces arbres de décision, les sols suisses se situent souvent dans la catégorie moyenne.
- La comparaison des rares données expérimentales disponibles avec les prévisions du modèle réglementaire EXPOSIT suggère que ce modèle pourrait ne pas être assez conservatif pour permettre une évaluation worst-case réaliste des risques de l'utilisation des PPh sur les terres agricoles drainées. Cependant, les données sont trop limitées pour permettre de tirer des conclusions fiables et générales pour la Suisse.

Mesures typiques visant à atténuer les pertes de PPh dues au drainage

- Le groupe de travail TOPPS a proposé diverses mesures d'atténuation et les a classées en fonction du risque de pertes défini dans l'arbre de décision. La plupart des mesures d'atténuation pour le niveau de risque faible font déjà partie des prestations écologiques requises en Suisse. L'évaluation du potentiel que chaque mesure d'atténuation représente pour la Suisse est indiquée dans un tableau.
- La plupart des mesures visant à atténuer les pertes par lixiviation réduiront également les pertes par les systèmes de drainage.
- Les mesures recommandées pour atténuer les pertes par ruissellement et par érosion sont généralement efficaces contre les pertes par drainage.
- Cependant, certaines mesures contre le ruissellement et l'érosion, comme le semis direct, peuvent avoir des effets à la fois positifs et négatifs sur les pertes par drainage. Par précaution, le semis direct ne devrait pas nécessairement être pratiqué sur les terrains plats et propices au drainage.
- D'après le modèle conceptuel et la littérature, l'optimisation de la date d'application est la mesure qui présente le plus grand potentiel en termes de réduction des pertes. Dans la pratique, la plage possible est toutefois limitée.
- Certaines mesures techniques d'atténuation telles que les milieux humides aménagés et le drainage contrôlé sont assez efficaces mais il n'est pas réaliste de vouloir les appliquer en Suisse. Des changements dans l'utilisation des terres pourraient être une piste, comme la paludiculture pour les cultures énergétiques, l'agroforesterie dans les zones humides, la culture du riz. Cependant, ces options sont soit des cultures de niche, soit moins rentables pour l'instant, que l'utilisation actuelle sous forme de terres arables drainées.

- Par conséquent, les mesures spécifiques de drainage sont rares et ne sont pas applicables à grande échelle.
- L’absence de mesures spécifiques et de cartes précises des zones drainées fait qu’il n’est pas réaliste de vouloir réglementer l’utilisation des PPh sur les terres drainées à l’aide de mesures spécifiques aux sites, contrairement à ce qui est déjà en place avec l’enregistrement des pratiques d’application de PPh dans le cas du ruissellement et de la dérive.

1 Introduction

Currently, around 2,000 tons of active ingredients of Plant Protection Products (PPPs) are used in agriculture in Switzerland every year (BLW, 2019). Measurements in small and medium rivers, including the NAWA-SPEZ program, have shown that numerous water bodies are contaminated with PPPs, particularly after intense rain events (Knauer, 2016; Spycher et al., 2019). PPP loss rates can vary by over an order of magnitude (Doppler et al., 2012). According to Kladivko et al. (2001), although losses via runoff and erosion tend to be highest of all pathways, losses up to 3% of the applied PPP can occasionally occur from drainage. In general, PPP losses from drainage are on average smaller than via runoff and erosion but higher than via leaching.

The Swiss „Action plan for risk reduction and sustainable use of plant protection products" considers under point 6.2.1.3 the development of strategies to reduce the input of PPPs into surface waters via agricultural drainage systems, via stormwater runoff from farm roads and driveways as well as via manholes on agricultural fields (The Federal Council, 2017).

The new measure presented below represents the basis for this project: *"Drainage can be an important input pathway into surface waters. There are currently no practicable regulations for reducing this risk within the PPP approval process. Measures to reduce inputs via drainage systems and their efficiency must be determined, and the significance of this pathway must be better investigated. This will provide the basis for measures to be taken as part of the PPP approval process or for implementation as good agricultural practice by farmers." "Measures to minimize the risks related to drift and run-off are currently being defined as part of the approval process for PPPs. This is not the case for drainage and stormwater manholes yet. The impact of these pathways requires further investigation and the development of effective mitigation measures"* (The Federal Council 2017, translated from the original German text).

The Federal Office of Environment (FOEN) and Agroscope pooled knowledge gaps in the field of drainage based on expert knowledge. Knowledge gaps were identified in four areas:

1. Basic mechanisms leading to PPP losses (conceptual model)
2. Geographical spread of drainage in Switzerland
3. Mitigation measures
4. PPP registration process

The specific aspect "geographical spread of drainage in Switzerland" was investigated by Agroscope in another sub-project. A comprehensive final report and a digital map of the drained areas of Switzerland are available (Koch and Prasuhn, in prep.). The present research project will focus on the others points and should deliver the following results:

- Development of a conceptual model for Switzerland for PPP transport to drainage. The model should show the relevant transport processes as well as the influencing factors (soil, PPP properties, etc.).
- Presentation of the main mitigation measures available to reduce PPP losses via drainage and assess their efficiency and feasibility in Switzerland.
- Assessment of the relevance of the regulatory model EXPOSIT.

Drainage can be an important entry route of PPPs into surface waters. There are currently no specific tools adapted to the Swiss agriculture and site conditions to assess the risk of PPP losses via drainages as well as suggesting mitigation measures against those losses. We present a conceptual model of PPP losses from drained fields into surface water, which focuses on Swiss conditions. It is based on literature and expert knowledge. The model should serve as the basis for the assessment of the importance of drainage losses of PPP into surface waters.

The effectiveness of the mitigation measures is assessed based on the conceptual model. In addition, we examined whether these measures also apply to Switzerland (site conditions, drainage types, legal requirements, etc.) and can be implemented. We suggest measures to be included in the PPP authorization process, as well as the implementation of some good agricultural practices with regard to PPP losses to surface water via drainage. Using data from a drainage field experiment in Switzerland, we evaluate the potential of the regulatory tool EXPOSIT to predict realistic worst-case losses.

This report is based on a comprehensive literature review following the work of Gramlich et al. (2018) who presented the effects of artificial land drainage on hydrology, nutrient and pesticide fluxes from agricultural fields. However, Gramlich et al. (2018) focused on the impact of drainage on hydrology than on the risk of PPP losses.
A lot of research has been carried out on preferential flow in soils (Jarvis et al., 2012; Weiler, 2017). The degradation and sorption processes have also been studied in depth for a wide variety of compounds (i.e. Wauchope et al. 2002).

There are a few good review papers on PPP losses via drainage, which summarize the state of knowledge and the results of numerous experiments (i.e. Kladivko et al., 2001; Brown and van Beinum, 2009). The applicability of those studies to Swiss agricultural conditions is however unclear.

2 Transport of plant protection products to agricultural drains

2.1 Fate processes of plant protection products

The main processes involved in the fate of PPP are adsorption, photo-degradation, microbial degradation, volatilization, transformation into metabolites and plant uptake. Those processes are controlled by parameters such as solubility, adsorption strength, and degradation rates of the main compounds and the formation fraction of metabolites. They are a function of temperature, moisture levels, pH, soil organic carbon and soil bacterial communities. Figure 1 illustrates the different processes that can affect PPP fate (Delcour et al., 2015). Adsorption, microbial degradation and photo degradation are the most important processes at the field scale. They all depend on temperature, while microbial degradation is also affected by soil water content (Bloomfield et al., 2006; Wauchope et al., 2002).

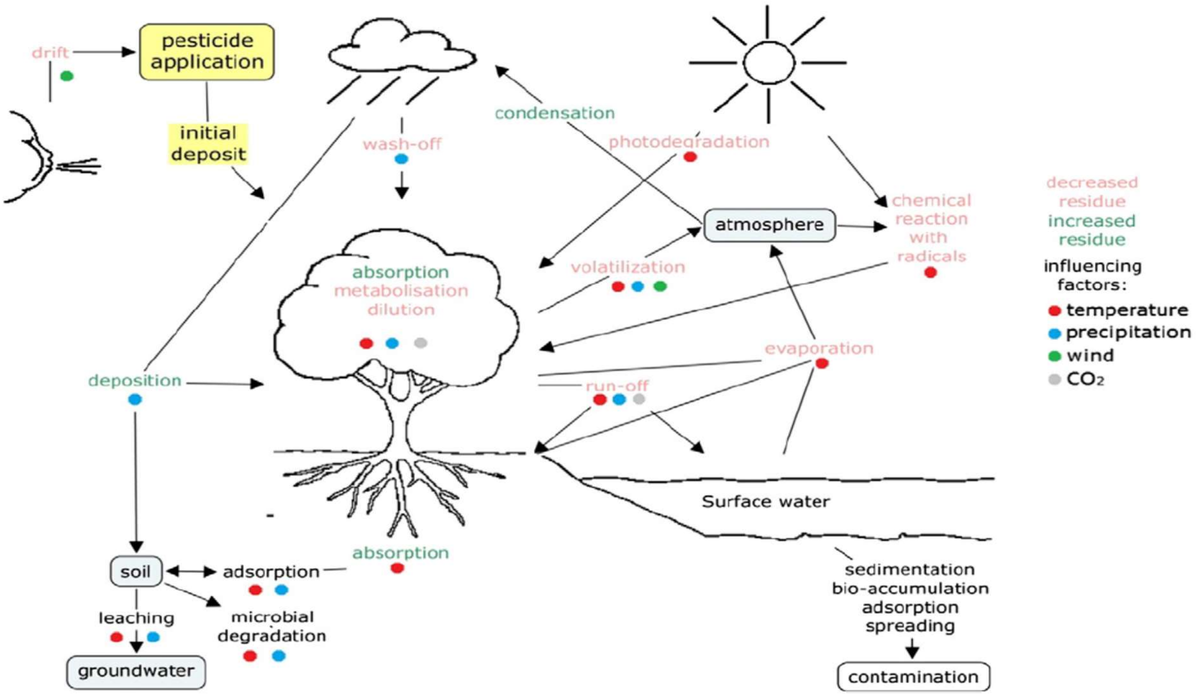

Figure 1: Processes Affecting the Fate of PPPs. (From Delcour et al., 2015).

2.1.1 Adsorption

Adsorption is the main process affecting the mobility of pesticides. Simo and Zhang (2002) point out that the major factors that affect the adsorption of a given pesticide in soil include the soil organic matter content, the soil properties (i.e., clay content, moisture content, porosity, permeability, pH of soil, etc.), the temperature of soil, the cation exchange capacity (CEC), and the structure of the chemical. They mention that soil organic carbon (SOC) has been proven to be the most important parameter. However, the fate of polar PPPs in soils, like weak acids, is an exception as it depends much more on soil pH than SOC content. The impact of pH is strongest for PPPs with a pK_a (acid dissociation constant) in the range of soil pH (Wauchope et al., 2002; Van der Linden et al., 2009). Delle Site (2001) presents a comprehensive review of sorption processes for organic compounds, including sorption isotherms and kinetics. Two parameters are used to quantify adsorption strength: soil sorption coefficient (K_d) and organic-carbon-normalized partition coefficient (K_{oc}).

Because K_d values depend on the fraction of SOC in the tested soil (f_{soc} in %), the sorption strength of a specific PPP is usually normalized to obtain K_{oc} ($K_{oc} = K_d / f_{soc}$).

Li et al. (2003) show that organic matter and clay minerals are generally considered as the two most important soil components in the retention of soil-applied pesticides. In particular, soil organic matter (SOM, usually taken as 1.72 times the SOC content) plays an important role in the adsorption of nonpolar organic compounds. The potential contribution of soil mineral fractions to adsorption can be important for some chemicals such as glyphosate (Albers et al., 2009; Vereecken, 2005). Adsorption is a dynamic process. Some chemicals will take more time to adsorb to soil particles than others. This kinetic adsorption can play a role if solutes are quickly transported through the soil to the aquifer. Because adsorption is driven by the gradient in concentrations between water and the sorbing material, kinetic sorption will decrease over time as the gradient diminishes (Gulkowska et al., 2016). In addition, for most compounds, equilibrium sorption decreases with increasing temperature (Steffens et al., 2013). Wauchope et al. (2002) present a comprehensive review of pesticide soil sorption parameters.

2.1.2 Degradation

Gregoire et al. (2009) point out that half-life times of pesticides in the environment are influenced by their reaction to abiotic processes (photolysis, hydrolysis, redox reactions) or biotic processes (biodegradation, conjugation, metabolization). Pesticides can degrade by oxidation or photolysis whether they are in solution or adsorbed to the solid phase. This can be catalyzed by soil components. Abiotic degradation is often incomplete and leads to metabolites, which may have a more severe eco-toxicological impact on the environment (Gregoire et al., 2009).

The impact of aquatic conditions and aerobic or anaerobic conditions can be very important on the half-life of pesticides. The degradation constant of thiaclopride can for example vary from three days in atmospheric conditions to one year in anaerobic aquatic conditions (Sage Pesticides, 2020).

2.1.3 Volatility

Volatility influences how much PSM remains at the soil surface (Mottes et al., 2014). Bloomfield et al. (2006) made a comprehensive summary of pesticide fate processes in a review article on the impact of climate change on the fate and behavior of pesticides in surface and groundwater. They note: "*cumulative volatilezation losses can range from a few percent to 50% of the applied dose, depending on the properties of the pesticide.*"

2.2 Surface hydrology

Gramlich et al. (2018) discussed in detail the impact of drainage on hydrology. We therefore keep the hydrology section short. We focus more on the interaction with PPP in terms of losses (section 2.4).

2.2.1 Terminology

Drainage and PPP transport via drainage: In the present report, drainage is understood to mean artificial, man-made drainage under agricultural land. These can be pipes, tile drains, mole drainage or open trenches (ditches The PPP losses happen via the overlying or laterally adjacent agricultural area through matrix flow or preferential flow (for further details see below, see also chapter 2.3 Soil hydrology). However, PPP can also get into such artificial drains via other entry paths. This can be e.g. shortcuts over inlets of road and field paths, farmyard and roof drainage or maintenance shafts of brooks. Because of those point sources, PPP losses do not always originate from fields. PPP transports in drainages always lead to a direct pollution of surface water and not groundwater. On drained areas, however, in addition to PPP drainage in surface water, PPP leaching into groundwater can also occur.

Figure 2: A drain discharging into a canalized small watercourse.

Figure 2 shows an engineered drain discharging into a watercourse. It is likely that this canal was created to serve as a draining ditch.

Figure 3: A drain probably discharging more water than just drained water.

Figure 3 illustrates that the drainage infrastructure is not necessarily separated from works redirecting small streams. The outflow in this figure is important and could be a mixture of drain-flow and a small stream higher up in the catchment.

Figure 4: A drain discharging into Chatzenbach, Canton Zurich.

Figure 5. A drain discharging into a small watercourse in Rueti, Canton Bern (photo: Urs Schönenberger).

In Figure 4, one can see how difficult it can be to associate a drain outlet to a specific field and crop.

Figure 5 shows a small pipe draining a relatively steep agricultural plot. In Section 3.3, we show that a surprisingly high percentage of drains may be installed on sloping land.

Runoff and PPP transport via runoff: The water flow path along the land surface is sometimes ambiguously referred to as surface runoff or overland flow. However, in the literature, this distinction is inconsistent, where either of the terms or even both are used (Bernet et al., 2017).

Reichenberger et al. (2007) explain different types of runoff generation as follows:
"Surface runoff can in principle occur on almost every arable field, even in nearly flat terrain; yet its frequency of occurrence will depend on the climate. There are essentially two types of surface runoff: Infiltration excess or "Hortonian" runoff is generated when both infiltration capacity and surface storage capacity of the soil are exceeded by the incoming precipitation. Infiltration capacity decreases with increasing silt and clay contents (lower saturated conductivity of the soil matrix), but increases with increasing soil structure and the presence of macropores at the surface."
"Saturation excess runoff occurs when the water table rises to the soil surface, in which case any rainfall onto the soil immediately runs off. Saturated areas typically form at the base of hillslopes, where soil moisture is high due to downslope movement of subsurface water ("interflow"), in soils with impermeable horizons, where a perched water table develops, and in areas of shallow groundwater."

We use the term runoff in this report because it is mostly used for PPP transport in the literature (e.g. TOPPS, 2018). Under PPP entries by runoff in rivers we mean here only the entry if the runoff leaves the plot and reaches the surface water directly or indirectly via manholes. Runoff, which arises, but also infiltrates on the plot will therefore not be considered as "runoff" with regard to PPP losses.

Preferential flow and macropore flow: Preferential flow is the overarching concept. It includes macropore flow as well as other fast transport processes through the soil such as finger flow. In German-speaking countries, the term "Makroporenfluss" is often confused with preferential flow ("präferenzieller Fluss").

2.2.2 Partitioning between surface runoff and infiltration

An important control on the losses of PPP to surface water via agricultural drainage is the way precipitation is shared between several hydrological flow pathways. The first aspect is the partition between runoff and infiltrated water. The processes controlling infiltration will be described in Section 2.3.

The French decision tool DPR2 (Guiet and Falchier, 2018) presents a decision tree that separates plots as mainly risky with regard to runoff if the slope is steeper than 3%. Gramlich et al. (2018) refer to a slope of 2% below which runoff is not relevant in practice. They however point out that such a slope threshold holds for land that is not drained. Depending on the drainage efficiency, a drained sloping field could generate much less surface runoff than a natural field, thereby increasing the infiltration to runoff ratio.

Large-scale topographical features can also have a significant effect on the partition between surface runoff and infiltration. If slopes converge to a bowl or a flatter zone, it is likely that most of the surface runoff that was initially generated upslope will pond and infiltrate because of the lack of outlet, or the significant change in slope gradient (Frey et al., 2009; Doppler et al., 2012). As the catchment scale increases, other loss pathways and sources (e.g. surface runoff, point sources) also contribute to the total contaminant loading. Leu et al. (2004a, 2004b) for example showed that point sources from farms produced the largest concentrations in the stream. Farmyard losses were short (<2h) and rare, contributing to less than 20% of the total losses but to the highest peak concentrations (Leu et al., 2004a). They also showed that diffuse losses dominated by preferential flow to tile drains and surface runoff, displayed surprisingly large spatial variability given the small size of the catchment (Leu et al., 2004b).

The intensity of rain events has a strong influence on the type of runoff that will take place. High intensity can lead to infiltration excess overland flow, whereas high amounts can later lead to saturation excess overland flow. A paper by Kladivko et al. (2001) points out that runoff typically leads to higher PPP concentrations in surface waters instead to losses via drainage. Their study however focuses on North America. In Switzerland, Siber et al. (2009) demonstrated the importance of mapping critical areas that have a high “fast flow index”. Those areas, if they coincide with zones of high pesticide use, would lead to high PPP losses via runoff and possibly drainage.

The timing of PPP losses via surface runoff and drainage depends mainly on the generating process. In case of infiltration excess, overland flow and surface runoff will be generated quickly. In parallel, if the soil is prone to macropore flow, the rain intensity required to drive infiltration excess will likely lead to preferential flow. Macropore flow (see Section 2.3) can be extremely rapid, in which case losses via surface runoff and drainage can discharge into surface waters at the same time.

In case of saturation excess overland flow, surface runoff is generated because the soil is fully saturated. This can happen on undrained- or poorly-drained land. In this case, preferential flow paths may have already contributed to PPP losses via drainage. Depending on the formulation of the PPP, it is possible that most of the PPP has been transported into the soil before surface runoff occurs. Surface runoff would therefore discharge later than drainage into surface waters and thus contribute less to PPP losses (Jarvis, 2007). If a PPP is starch encapsulated, this can be the contrary if the initial rainfall is sufficient to dissolve the starch shell (Davis et al., 2018).

Water flow into tile drains is less diluted with clean water than water in the saturated zone below the drains. If water with high PPP concentration flows down macropores of a few meters of a drain (flowing directly into a drain rarely happens), it will indeed be less diluted with clean water than water that has travelled through tens of meters of saturated soil matrix. PPP concentrations are therefore higher when macropore flow is preponderant.

A fully saturated soil on a drained field is only possible if the tile drains do not function, except if a confining layer such as a plough pan has built up above the drains. If the groundwater table excessively raises above the drains, it would mean that the outflow is not quick enough, or that the drains are not close enough in relation to the hydraulic conductivity of the soil.

2.3 Soil hydrology

2.3.1 Seasonal dynamics in drainage flow-paths

The general hydrogeological behavior at each field site needs to be taken into account to understand drainage outflow dynamics. Jacobsen and Kjær (2007) compiled a literature review where they evaluate whether pesticide concentrations in drainage water are representative of root zone leaching of pesticides. They conclude that: *"drainage water concentrations are not necessarily representative of leaching concentrations on very well-drained soils and on poorly drained soils with little capacity for lateral transport beneath the plough layer"*.

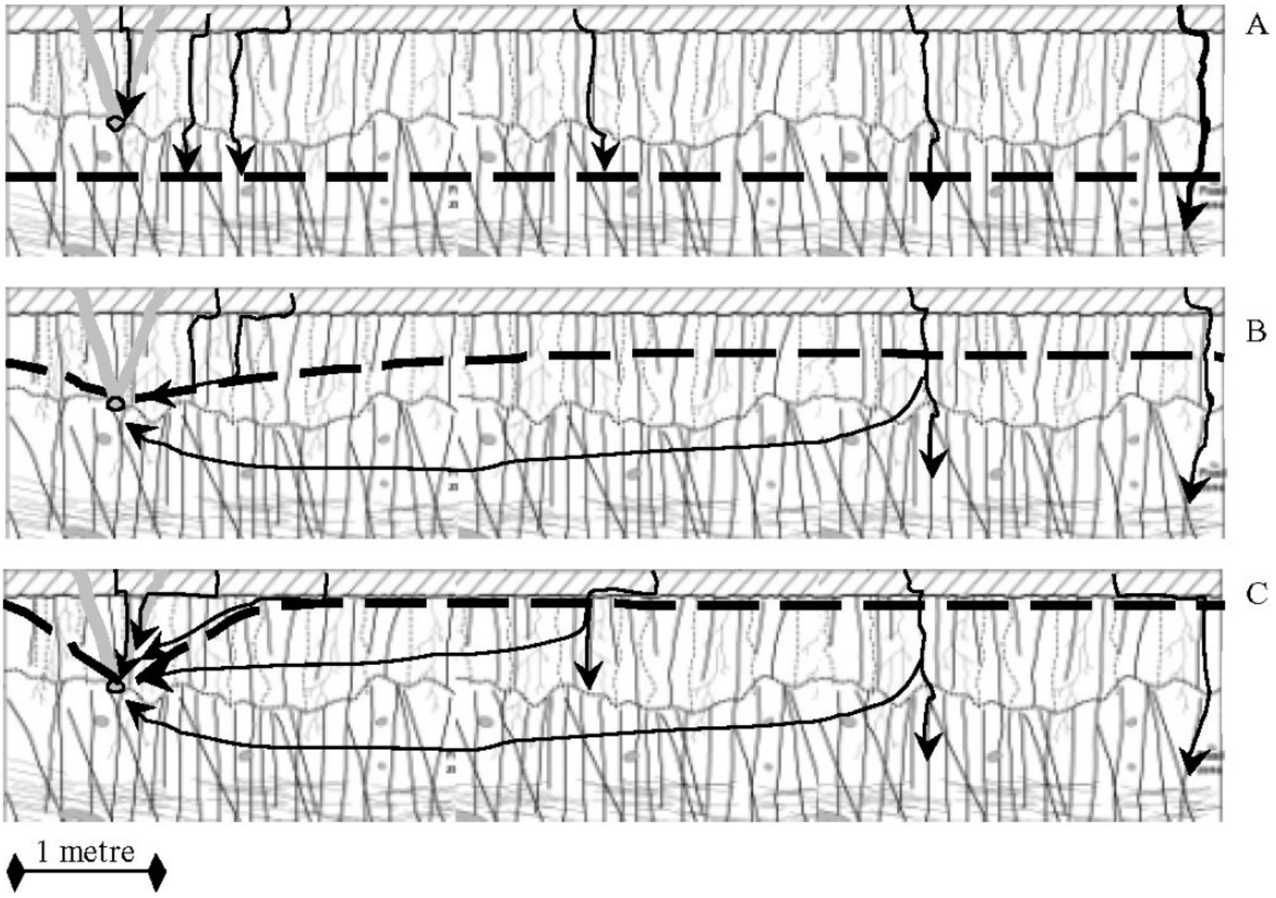

Figure 6: Different pathways (solid lines) that dominate drainage water flow under different hydraulic conditions. The dashed line represents the water table, the small circle is the tile-drain. A: low drain-flow situation. The water table is below the drain. B: Both matrix flow and preferential flow contributions. C: The water table has reached the plough pan. There is much preferential flow contribution. Figure adapted from Jacobsen and Kjær (2007).

Relatively porous soils and moderate climatic conditions can lead to similar drainage water and leaching water concentration. Drainage and leaching concentrations will be more comparable in the case of weakly sorbing pesticides than for strongly sorbing pesticides. Jacobsen and Kjær (2007) looked at the seasonal dynamics of flow pathways to drainage and groundwater. Figure 6 presents the various pathways that can conduct water to the drains, depending on the season and hydrogeological context. When the drain is not active and the water table is below the depth of the tile drain, transport is dominated by vertical flow through the soil profile (Fig. 6a). Flow into the drain will only happen if macropores are directly connected to it, which is unlikely. Saturation at drain depth is required to “force” water into the drain, for example if a stagnant soil layer is present above the groundwater table. However, if the hydraulic conductivity of the unsaturated soil surrounding the drain is low, some of the water will not re-infiltrate from the drain but will flow to the outlet.

For example, in Villholth et al. (1998) a heavy storm event induced drain flow although the groundwater table was 0.9 m below drain depth. Kjær et al. (2011) reported a similar behavior. In both cases, the quantitative effects in terms of the water balance were minor. The effect on PPP concentrations could however be high, especially considering the lack of dilution via this flow path.

When the water table reaches the drain depth during wet periods, water will start to move laterally into the drain (Fig. 6b). If precipitation is moderate, drainage will consist mainly of matrix flow originating from depths around drain depth. If precipitation is intense, the water table between drains will momentarily rise (Fig. 6c) and drainage flow will peak. In this case, drains will mainly be fed from depths above the tile drain via lateral flow paths. Drainage water will then be a mixture of infiltration through the backfill material directly above the tile drain and lateral flow from the elevated aquifer water table.

How drainage influences leaching of PPP to groundwater depends, among other factors, on the level of the groundwater table. If a perched water table develops (impeding low permeability layer, but deep regional groundwater level), drainage will have a limited impact of leaching, with a potential small reduction. If the groundwater level is higher than the drain during the season of active drain-flow, then leaching to groundwater will be strongly reduced, as contaminated groundwater will be quickly evacuated to surface water via the drainage system (Jacobsen and Kjær, 2007).

2.3.2 Infiltration processes: matrix flow and preferential flow

Infiltration is a non-linear function of several factors such as soil properties, slope, antecedent moisture conditions and surface roughness. The Green-Ampt equation is an approach based on the Darcy equation and considers an exponentially decreasing infiltration rate (Skaggs, 1978). Other approaches are more conceptual, such as the Runoff Curve Number (CN), which is a calibrated parameter, based on land use and catchment properties (Mottes et al., 2014; Adriaanse et al., 2017). It is not a function of time as opposed to the Green-Ampt approach.

In the previous section, we discussed the partition between infiltration and runoff. We now present processes that affect infiltration. Kördel et al. (2008) provide a good summary of many studies discussing infiltration as matrix flow and preferential flow. Figure 7 shows the different flow paths precipitation can take.

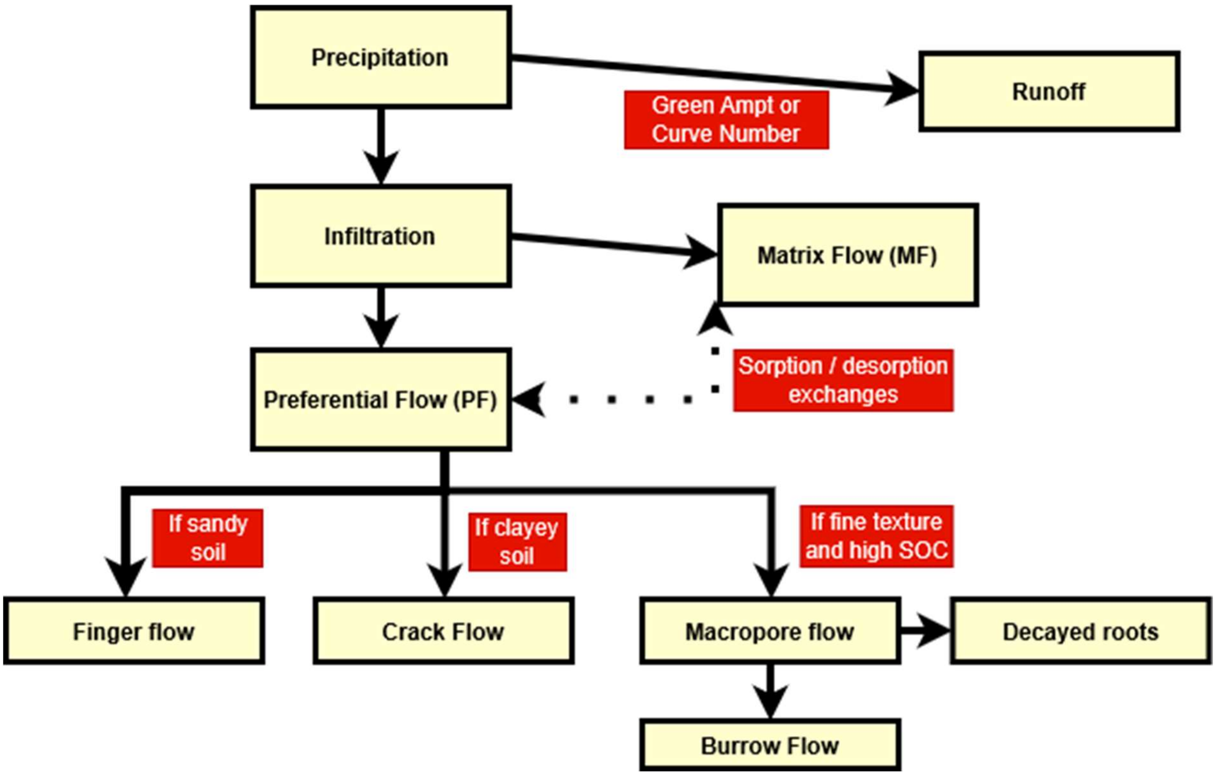

Figure 7: Different possible flow paths into drains for precipitation. The dotted line represents the interaction between matrix flow and preferential flow.

Preferential flow in soils is the rule rather than the exception (Flury et al. 1994; Weiler, 2017). However, if preferential flow represents a minor part of soil water flow, then surface runoff will likely be the most important pathway of PPP losses and will also contribute much earlier to streamflow than drainage originating from matrix flow (Gramlich et al., 2018). Preferential flow means that water (and its solutes) bypasses parts of the bulk soil matrix, resulting in a faster than average movement of water. Flury (1996) notes that preferential flow is not used in a consistent manner in the literature. As illustrated in Figure 8, there are different factors that trigger preferential flow such as:

- Macropores: biopores (earthworm burrows, (former) root channels), shrinkage cracks.
- Structured textural heterogeneous porous formations (e.g. dense aggregates in the plow layer caused by plowing).
- Unstable flow (fingering flow: water repellency, air entrapment, textural layering). Those are not often relevant in Switzerland.
- Funnel flow: lateral redirection and funneling of water caused by textural boundaries (e.g., plow layer with biopores).
- Finger flow: a form of preferential flow through the soil matrix in homogeneous sandy soils.

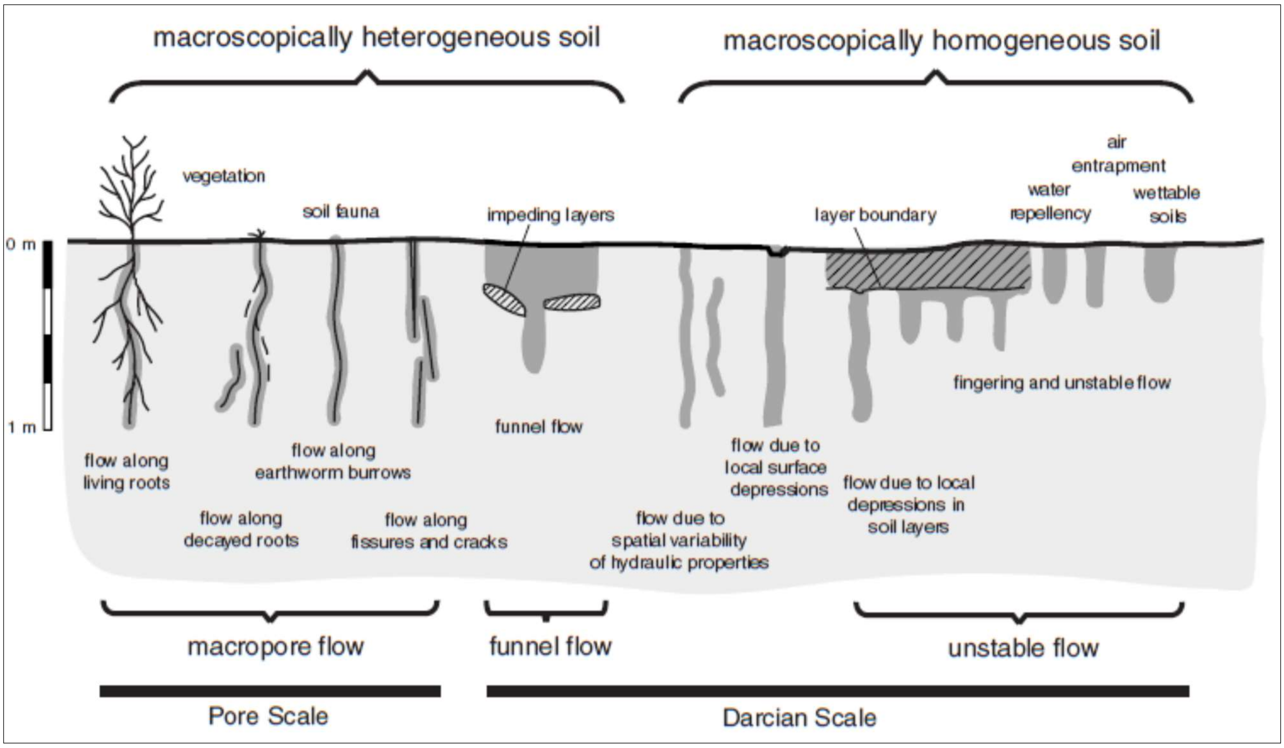

Figure 8: Schematics showing different preferential flow mechanism observed at pore and Darcian scale (from Hendrickx and Flury, 2001).

Pore water in soils is captured by capillary forces (matrix potential). At field capacity (maximum water-holding capacity), only small pores are water-filled, while the larger pores are drained and filled with air. As the water-filled pore space involved in the flow process decreases, when the soil becomes drier, the hydraulic conductivity is also reduced. The finest pores show a very low hydraulic conductivity and thus do not contribute much to the solute movement. They can however retain pesticides by diffusion or upon filling, which binds them to a rather immobile water phase.

Pores with the smallest diameter will fill up with water first, followed by the pores with the next smallest diameter. This process goes on until the infiltration capacity of the soil matrix is reached. At this threshold, the soil matrix is locally saturated and if precipitation is larger than the infiltration capacity of the soil, macropores, if present, will conduct water and preferential flow will occur. Macropores are wide enough to conduct water, irrespective of whether the bulk of the soil matrix is saturated or unsaturated. Local saturation of the soil surface at the millimeter scale is however required to activate flow through macropores. Therefore, the more the soil is saturated, the more likely macropore flow will happen, but matrix flow will also then be an element of the total flow. The drier the soil, the higher rain intensity will be required to initiate macropore flow, but the higher the relative contribution of macropores to infiltration will be (Shipitalo et al., 2000).

Macropore flow is most important for silty, clayey, and loamy soils (also called structured soils) because they have few medium-sized pores and therefore a relativity low hydraulic conductivity through the matrix (Ghafoor et al., 2013). In loamy and silty soils, macropores mainly form as biopores from decaying taproots and earthworm burrows. Stable macropores, for instance, are much more likely to be formed by decaying taproots of alfalfa than by the fine and fibrous roots of wheat. Macropores formed by earthworm burrows can have various sizes and depths depending on worm species and their abundance (see Table 4 in Kördel et al., 2008). In clayey soils, macropores are often formed by cracks and fissures upon drying (Dadfar et al., 2010a). Loamy soils may also develop shrinkage cracks (see Figure 24). Biopores are more stable than cracks upon rewetting (Kördel et al., 2008). During heavy rainfalls, macropores become active and can transport water directly to the deeper soil horizons.

Matrix flow is most important for sandy soils because their saturated hydraulic conductivity is high and earthworm burrows are not abundant in these soils (Lindahl et al. 2009; Dadfar et al., 2010b). Finally, drained organic soils can develop shrinkage cracks, sometimes invisible at the soil surface, as they dry out and degrade (for more details see Holden et al., 2006 and Gramlich et al., 2018). Holden et al. (2006) point out that this can lead to the development of a "pipe network" (connected cracks) across drained hillslopes.

Macropore flow can bypass unsaturated soil sections and bring water directly to the drain and/or the water table. Kördel et al. (2008) found that preferential flow can be 100–400 times faster than matrix flow in experiments using large lysimeters, where the macropores can drain freely. Flow rates would be much lower if macropores are not open-ended or end in a saturated subsoil. Matrix flow alone is 20 to 50 times less conductive than total flow including macropores. The flow velocity also depends on the amount of water supply by heavy rainfall and on the number and diameter of the active macropores. The authors report a range from 70cm d^{-1} to 220cm d^{-1} and stress that such high flow rates occur only in open-ended macropores. The volume of macropores depends on several factors that vary in space and time. This volume however remains low compared to the bulk of the matrix. Kördel et al. (2008) mention studies where macropore volume did not exceed 6% of total porosity, although soils contained high numbers of earthworms.

Matrix flow and macropore flow can naturally occur simultaneously during heavy rainfalls. They contribute to the total vertical water flow with different ratios depending on rain intensity and duration, infiltration capacity of the soils, macropore characteristics, and inhomogeneity in soil profile (Kördel et al., 2008). In the mainly loamy Swiss soils, macropores are the most extreme case of shortcut from the soil surface to the groundwater and have therefore the largest impact on drainage discharge. In Dutch clayey soils, Scorza et al. (2004) found evidence of preferential flow during wet periods although no shrinkage cracks were observable at the soil surface. The preferential flow was probably caused by permanent macropores that were observed in the 30–100cm layer. During the first drainage event, concentrations of PPP in drain water were an order of magnitude higher than in the groundwater at 100–120cm depth. This illustrates the important potential impact of drains on peak concentrations in small watercourses. Kördel et al. (2008) note that after heavy rainfalls, water flow in drains often start long before saturation of the whole soil. The heterogeneity of the macropore system in silty and clayey soils leads to non-uniform flow through the soil with highly variable velocities.

As stated by Nimmo (2012), an increase in antecedent moisture will likely allow more of the smaller pores to contribute to infiltration and water movement, thus reducing the contribution of macropore to total flow. The same author, however, notes *"this doesn't imply that preferential flow cannot become greater with increasing wetness. Observations suggest that many processes of preferential flow are enhanced by greater wetness. However, evidence as cited in this commentary shows there are important situations where preferential flow is enhanced by relative dryness."*

Further information on preferential flow can be found in the FOOTPRINT "State of the art review on preferential flow" (Jarvis and Dubus, 2006) and in the later review by Guo and Lin (2018). The "summary of current understanding" by Jarvis and Dubus (2006) can be found in the Appendix (A.2). The FOOTPRINT project (Dubus et al., 2009) suggests that soil compaction will lead to more pronounced non-equilibrium flow and therefore to more solute transport. For example, Kulli et al. (2003) showed that sprinkler irrigation on compacted soil resulted in surface ponding and strong preferential solute transport into the subsoil, primarily through earthworm burrows. Although worm channels were also present in the control plot, most of the applied water infiltrated without ponding. The more densely distributed macropore system, which had been degraded in the compacted plot, was conveying the flow as opposed to earthworm burrows.

2.4 Interaction between hydrological flow paths and PPP properties

Soil-solute transport processes are complex as stated by Alvarez-Benedi and Munoz-Carpena (2005). The main processes controlling the transport of solutes in porous media are convection (also called advection), hydrodynamic dispersion, interphase mass transfer and transformation reactions. Adsorption and volatilization are the types of phase changes possible.

"Four main factors can be responsible for non-ideal transport:

1. *Physical non-equilibrium: solute transport is strongly affected by heterogeneous soil hydrology.*
2. *Rate-limited (or kinetic) adsorption: most organic compounds do not sorb instantly. Sorbing rates are also very variable.*
3. *Non-linear adsorption isotherm*
4. *Field-scale heterogeneity: The influence of spatially variable hydraulic conductivity on water flow and solute transport at the field scale generates apparent values of longitudinal dispersivity, which are much larger than those observed in soil columns"* (Alvarez-Benedi and Munoz-Carpena, 2005).

Based on those aspects, we see that heterogeneous hydrological pathways such as macropores or larger field-scale heterogeneities will have an impact on the time available for sorption of PPPs.

2.4.1 Share between losses via preferential flow and matrix flow

The interaction between micropores and macropores has an impact on solute transport. If the rain intensity is small enough, small pores with become water-saturated first, and macropores last. Solute flux density is much greater in larger pores than in smaller or medium pores leading to an uneven distribution of dissolved substances in the soil profile. Kördel et al. (2008) further stress that solute transport is much faster if antecedent soil moisture is high. They assert that the flow will take place directly through large pores, bypassing fine pores already filled with rather immobile water.

Kördel et al. (2008) however points out that if macropore flow dominates total flow during an intense rain event on unsaturated soil, the dilution of applied PPPs will be low and high concentrations could reach the drains. Such significant transport occurs at the beginning of the first flow event after PPP application while later events will transport much lower amounts.

Lewan et al. (2009) showed that the main contribution to peak losses via drainage is flow through macropores. The amount of PPP transported through matrix flow is however likely to be much lower as the flow is much slower and leaves more time for adsorbing chemicals to degrade. Desorption will have a small impact on the temporal dynamics of PPP leaching throughout the season. The compounds will desorb with time but this will lead to rather small concentrations compared to the initial leaching event. Kladivko et al. (1991) indeed mention that desorption is not rapid enough to sustain high concentrations of PPP when new water flows through macropores. It is therefore not a significant process in combination with macropore flow.

If preferential flow pathways are regularly flushed with water, at least the water phase will be depleted with PPP (Kladivko et al., 1991). This depends on the rate coefficient of desorption (depends on the compound) how fast the adsorbed PPP, if available, is released to the liquid phase. In addition, PPP from outside preferential flow pathways can enter this region by diffusion or lateral flow processes.

Shipitalo et al. (2000) suggest that in medium- and fine-textured soils most of the water that moves to the subsoil during the growing season (May to October) is probably transmitted by macropores: "*If a heavy, intense storm occurs shortly after surface application of an agricultural chemical to soils with well-developed macroporosity, the water transmitted to the subsoil by the macropores may contain significant amounts of applied chemical, up to a few per cent, regardless of the affinity of the chemical for the soil. This amount can* *be reduced by an order of magnitude or more with the passage of time or if light rainstorms precede the first major leaching event. Because of movement into the soil matrix and adsorption, solutes normally strongly adsorbed by the soil should only be subject to leaching in macropores in the first few storms after application."*

In complement to the processes mentionned by Shipitalo et al. (2000), particulate transport may be important for strongly adsorbing compounds as illustrated in Figure 9. Torrentó et al. (2015) noted the impact of both macropore flow and matrix flow on the concentrations measured from the outlet of 12 lysimeters at Reckenholz, Switzerland. With a well-drained sandy-loamy Cambisol, they recorded two peaks for a pesticide (acetochlor), which suggests that both preferential and matrix flow lead to losses.

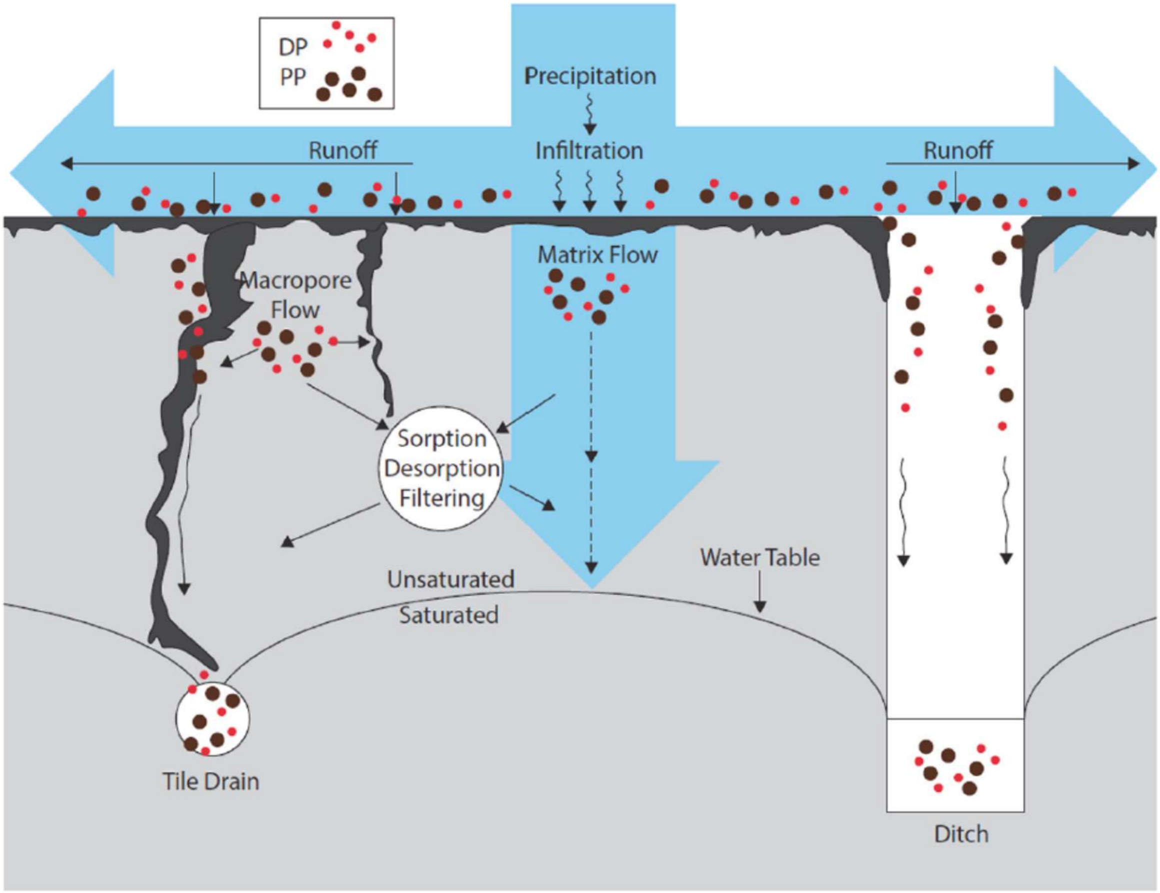

Figure 9: Flow diagram of water and P partitioning in artificially drained systems. DP is dissolved P and PP, particulate P (from Radcliffe et al., 2015).

Figure 9 illustrates how phosphorus (P) losses depend on the interplay between hydrological flow paths and sorption properties. The fate and behavior of phosphorus under these circumstances is very similar with PPPs, except that degradation mechanisms are quite different and the variety of compounds leads to a wide variety of responses. Precipitation either infiltrates or causes surface runoff. The infiltrated fraction can infiltrate as macropore flow or matrix flow. There are sorption and desorption interactions between macropores and the matrix. Finally, the raise in the groundwater tables brings infiltrated water laterally towards the drains or open ditches. Note that a macropore that directly "falls" onto a drain is rare.

It is difficult to generalize but some studies, such as Kladivko et al. (2001), suggest that the sum of surface runoff and drainage losses tends to be smaller than losses via surface runoff only, in the absence of drainage. The concentration may nevertheless not be smaller, as there could be less flow for quite high losses in the case of drained land, if preferential flow dominates. In the specific case of no-till, Shipitalo et al. (2000) found that less than 1% of the total precipitation was lost to surface runoff whereas almost 17% of the precipitation left conventionally tilled fields as surface runoff. Agricultural practices substantially improving infiltration, such as no-till, may therefore increase the proportion of PPP losses via drainage.

The amount of sorbed chemicals (PPPs and their transformation products) will strongly depend on the infiltration flow paths. If preferential flow in the form of by-pass flow happens (through large cracks), adsorption will be negligible and high losses could happen.

Adriaanse et al. (2017) discuss the impact of adsorption strength on surface runoff concentrations for fields that are runoff-dominated and not drained. Runoff concentration decreases with increasing runoff for weakly sorbing compounds. For weakly sorbing compounds, runoff events lower than 1mm cause highest stream concentrations. On the other hand, for strongly sorbing PPPs, runoff concentrations do not really depend on runoff size.

If an area that used to create much runoff because of saturation excess overland flow is drained, drainage will likely become the most important loss pathway. Kladivko et al. (2001) however concluded that drainage concentrations and total PPP fluxes were up to one order of magnitude lower than those of surface runoff for artificially drained catchments. They highlighted that although subsurface drains created an additional flow path for PPPs, the reduced losses via surface runoff were always greater than drainage losses.

Smaller losses to drainage will take place with wider spacing of drains because the overall amount of water removed will be lower. The amount of leaching losses to groundwater will increase.

2.4.2 Impact of PPP properties on losses via drainage

The organic coating of macropore walls can be hydrophobic, which would diminish adsorption (i.e. Klaus and Zehe, 2011; Jarvis, 2007) and contribute to bypassing large parts of the soil matrix, thereby reducing the effect of adsorption strength on PPP losses via drainage. On the other hand, the walls of biopores can present higher sorption capacity than bulk soil due to higher SOC content. Another important aspect is that preferential flow can be too fast for sorption to fully occur. The fast flow of water through macropores can decrease the importance of sorption processes if those are slow with respect to the specific time scale of water flow.

The most soluble and persistent PPPs with low adsorption properties will be transported to surface water via drainage. This is especially the case if matrix flow is dominant. If preferential flow happens through large cracks as “by-pass” flow, soil particles can be entrained into the drain. This would allow strongly sorbing PPPs to reach the drain. Jarvis (2007) has shown that the PPPs, which were least likely to reach drains as a function of adsorption, were the PPPs displaying medium K_{oc} values, as they have a medium mobility and might still be diluted by surface runoff.

Highly mobile PPP can get stuck in the soil matrix. This leads to a reduced leaching variability as a function of adsorption properties. PPPs used in agriculture have widely contrasting physico-chemical properties. Jarvis (2007) notes that this makes it difficult to generalize about the effects of macropore flow on pesticide leaching. The occurrence of macropore flow should however strongly increase the losses of otherwise ‘non-leachable’ (i.e. strongly sorbed or fast degrading) compounds. It will on the other hand have less effect on highly mobile or persistent compounds (Larsson and Jarvis, 2000). Indeed, in a few cases, macropore flow may actually decrease pesticide leaching. For instance, Larsson and Jarvis (2000) showed that the losses of the highly mobile herbicide bentazone through tile drains in a structured clay soil was reduced by approximately 50% due to macropore flow. After application, most of the chemical had moved into the soil matrix. There, it was somehow isolated from water flowing in macropores and would only move with a reduced velocity through the matrix. Consequently, differences in drainage losses between PPPs that span a wide range of adsorption properties are significantly reduced in the presence of macropore flow.

Adsorption properties differ between substances and also depend on parameters such as soil organic matter, clay content and/or pH (Wauchope et al., 2002). The fraction of PPP mobilized depends on complex sorption processes. A high sorption coefficient K_{oc} will additionally reduce losses much less when macropore flow is dominant than matrix flow, due to particle-facilitated transport of PPPs (Jarvis, 2007).

According to Larsson and Jarvis (2000), the relationship between losses via drainage and K_{oc} is not necessarily linear, which would warrant more than two categories. Due to potential entrainment of soil particles though large macropores (rather cracks than biopores), highly sorbing PPPs could actually leach via drainage more actively than compounds with medium adsorption properties. De Jonge et al. (1998) found that colloidal material in the size fraction of 0.02 to 0.24 µm contributed between 3 and 9% of pesticide leaching, while 3 to 13% originated form colloids larger than 0.24µm. This is a major difference with leaching losses, which are very sensitive to the adsorption coefficient, the Freundlich exponent and the transformation rate (Boesten, 1991). Figure 10 illustrates how the distribution and transmission layer in agricultural soils is controlled by the effect of plowing.

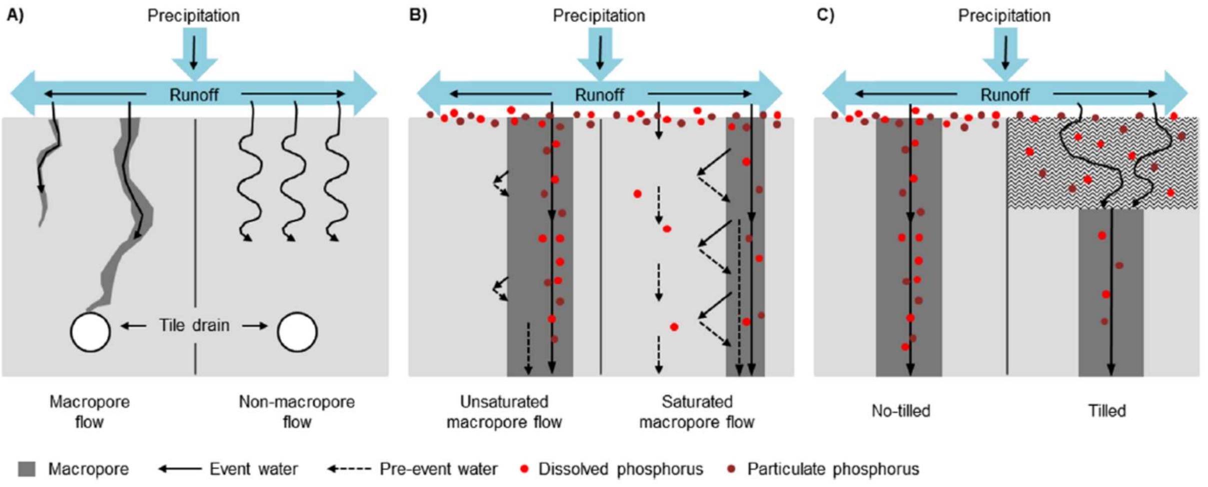

Figure 10: Effect of tillage on macropore flow and phosphorus transport to tile drains (from Williams et al., 2016). A) Macropore and matrix flow. B) Unsaturated and saturated macropore flow. C) No-tilled and tilled soils. Matrix flow is predominant in the tilled layer.

2.4.3 Typical PPP losses from the literature

Data relating to PPP loss percentages via macropores and through tile drains vary in the literature. Kördel et al. (2008) exhaustively summarized the literature (see Table 9 in Kördel et al., 2008). They reported losses of applied PPP by macropore flow for a wide variety of PPPs. (i.e., up to 3.6% for atrazine, 2.3% for metolachlor, 1.1% for carbofuran).

In Table 1, we list losses of PPP in Switzerland and the world from lysimeter experiments, drainage-specific experiments and from catchment-scale experiments (measurements in small streams integrating all pathways: runoff, drainage and point sources). Losses recorded in lysimeter experiments and drainage experiments are very similar to those presented in Kördel et al. (2008).

Some studies have focused on measuring the ratio between PPP losses after only a few precipitation events, against total losses. Leu et al. (2004b) reported, for atrazine, dimethenamid and metolachlor, a ratio of more than 80% after 2 rain events. McGrath et al. (2010) measured, after four rain events, loss ratios of 63.1% and 49.2% for methabenzthiazuron and ethidimuron, respectively. This shows that the rain events immediately following application have the most impact on PPP losses.

Table 1: Losses as a percent of applied PPPs. Examples from the literature.

Experiment type	Chemical compound	Losses (%)	Reference	Comment
Lysimeter	Atrazine	0.2-1.2	Torrentó et al., 2018	Total losses
	Atrazine (depth injected)	2.3-2.4	Torrentó et al., 2018	Total losses
	Chloridazon losses as metabolite DPC	0.5-0.13	Melsbach et al., 2020	Total losses
	Ethidimuron	1.7	Kasteel et al., 2010	Total losses (2.5 years)
	Methabenzthiazuron	1.4	Kasteel et al., 2010	Total losses (2.5 years)
Various (author selec.)	Various compounds	up to 3.6%	Kördel et al., 2008	Losses by macropore flow
Drainage	Various compounds	0.5-3	Kladivko et al., 2001, Tournebize et al., 2017, Gregoire et al., 2009	Total losses
	Imidachloprid	0.48	Wettstein et al., 2016	Total losses
	Thiametoxam	1.20		
	S-metolachlor	0.032		
	Epoxiconazole	0.013		
	Kresoxim-methyl	0.003		
	Kresoxim-methyl acid (metabolite)	0.17		
Catchment-scale	Atrazine, dimethenamid, metolachlor	0.01-0.6	Leu et al., 2004b	Total losses
	Isoproturon (dry weather)	0.5	Doppler et al., 2014b	Total losses
	Atrazine, S-metolachlor (wet weather)	0.16-0.26	Doppler et al., 2014b	Total losses

2.5 Existing physical / computational models

Vanclooster et al. (2005), Mottes et al. (2014) and Jarvis et al. (2016) provide a good overview of the available models dealing with solute transport through soils and with preferential flow.

Alvarez-Benedi and Munoz-Carpena (2005) present a particular overview of the currently available pesticide leaching models (LEACHM, MACRO, PEARL, GLEAMS, PELMO, PRZM-3, and VARLEACH). SWAT is a generally conceptual model that has also been used to predict concentrations of PPPs entering surface waters (Brown and Hollis, 1996), including via drainage. Conceptual models focusing on tile drainage have been suggested by Steenhuis et al. (1997) as the “TAM-MO-DEL” or Branger et al. (2009) who propose modelling approach for pesticide transport in a tile-drained field called PESTDRAIN. Specific models have also been developed for preferential flow through clay cracks (i.e. Armstrong et al., 2000). Weiler (2017) mentions that macropore models can be used but are difficult to parametrize. Finally, machine learning approaches have also been tested to model water outflow from tile-drained agricultural fields (Kuzmanovski et al., 2015).

2.6 Registration model: EXPOSIT

2.6.1 Model description

The models used in the registration of PPP to assess their concentration in surface water range from simple models based on a set of rules, such as the German EXPOSIT model, to parameters-demanding process-based models, such as those used in the framework of FOCUS scenarios at the EU level (e.g. FOCUS, 2001). Within this framework, process-based models are used to assess the surface water exposure via different entry pathways for predefined scenarios. For drainage, the MACRO model calculates the drainage inputs, which are used by the surface water fate model TOXWA to predict environmental concentrations in surface waters (stream, ditch or pond). In Germany, a spatially and temporally probabilistic method for drainage exposure is under development to assess edge-of-field losses of PPP using statistically reliable percentile-based selections of soil-climate scenarios (Bach et al., 2017).

An example of a more simplistic regulatory tool is EXPOSIT (UBA, 2017; Grossmann, 2008), which was developed for the national registration of PPP in Germany. EXPOSIT uses a set of fixed loss factors to evaluate the surface water exposure from pesticide input via drainage. These loss factors were derived from field trials in Germany (UBA, 1996). According to the model documentation (Grossmann, 2008), pronounced drainage fluxes were mainly observed when the soil was saturated with water in autumn, winter and early spring. These fluxes were associated with preferential flow pathways (earthworm burrows, root channels, dry cracks, etc.). The losses via tile drains amounted up to 1% of the applied amount of PPP depending on the substance properties. In particular, moderately degradable, mobile PPPs may be associated with a high risk to losses by tile drains. In contrast, this risk is comparatively low for rapidly degradable or strongly adsorbed PPP. An implicit model assumption is that preferential flow is less dominant in late spring and summer, due to less precipitation and increased evapotranspiration during the vegetation period, so that PPP losses via tile drains are less critical in this period.

In the model, the PPPs are applied to an agricultural field with a size of 1ha. The application rate is corrected for the crop interception. After application, the substance resides three days by default in the soil, where it is degraded according to first-order degradation kinetics, before a heavy rainfall event starts the drainage event to a standard water body. For metabolites, the time to the heavy rainfall event is set to zero days by default.

The intensity of the heavy rainfall event amounts 20mm/day, including a 9mm storm event with a duration of 15 minutes to include particle-bound PPP from the treated area. According to the documentation (Grossmann, 2008), this storm event has an occurrence frequency of once a year. The standard water body directly borders at the field (edge-of-field concept) and measures 100m length, 1m width and 0.3m water depth. During the precipitation event, the water in the ditch is assumed to flow, resulting in the dilution of the concentration in the ditch by a factor of two, independent of the hydrological conditions.

The model distinguishes between total and peak losses by tile drains into a ditch: Total losses include losses from all drainage events following the application during a season. Peak losses, also known as the initial predicted environmental concentration in the ditch, are assigned to the above-mentioned heavy rainfall event 3 days after application. A model assumption is that 5 or 50% of the rainfall volume ends up as drain flow volume in the ditch during spring/summer resp. autumn/winter. Based on the findings in the German field trials, constant loss factors were defined for two mobility classes (more mobile: K_{oc} < 500mL/g and less mobile: K_{oc} >> 500mL/g) and for two seasons (spring/summer vs. autumn/winter). These factors are summarized in Table 2. Note that (i) the amount of soil residues at the time of the heavy rainfall event is used as reference for the percentages of total losses, and include a degradation period (not for metabolites) and (ii) that peak losses are calculated using a predefined percentage of total losses (12.5 or 25% depending on the season) divided by volume of water in the ditch, which is composed of the drainage volume (10 or 100m^3 depending on the season) and water volume in the ditch (30m^3).

Total losses increase by a factor of 20 for more mobile substances (K_{oc} < 500 mL/g) compared to less mobile substances (K_{oc} >> 500 mL/g) and by a factor of 5 for autumn/winter applications compared to spring/summer applications. Peak losses, expressed in % of the soil residues at t_{ref} = 3 days after application, are 10 times higher in autumn/winter compared to spring/summer, whereas the peak concentrations are only roughly 3 times due to the seasonal difference in drainage volumes higher (the exact number is 40/13, which is calculated as 10 times the dilution factor in the ditch with no flow (= 40m^3 / 130m^3) or with flow (= 80m^3 / 260m^3)). This results in different dilution factors in the ditch.

Table 2: Loss factors, expressed as the percentage of the soil residues at the time of the heavy rain event (default is 3 days), for PPP via tile drains into small surface waters (ditches) depending on mobility of the substance and the season of application.

		Season	
		Spring / Summer (1.4 – 31.10)	**Autumn / Winter (1.11 – 31.3)**
Mobility	Drainage volume, in % heavy rainfall volume (= 200m^3)	5% (= 10 m^3)	50% (= 100 m^3)
K_{oc} >> 500mL/g	Total loss	0.01%	0.05%
	Peak loss	0.00125% (= 12.5% of total loss)	0.0125% (= 25% of total loss)
K_{oc} < 500mL/g	Total loss	0.2%	1%
	Peak loss	0.025% (= 12.5% of total loss)	0.25% (= 25% of total loss)

2.6.2 A field study

EXPOSIT should provide worst case estimates of the initial concentration in or of the total losses to a small surface water body (ditch) after a storm event due to drainage flow for German conditions in agriculture. Principally, the applicability of this approach can be verified by designed field experiments. We exemplarily prove this for the drainage study of Wettstein et al. (2016), who monitored the concentration of several PPP in subsurface tile drain water (not in the ditch itself) during one growing season of sugar beet (*Beta vulgaris* L.) at an experimental site in Zürich-Affoltern, Switzerland. The treated field measured 100 × 44m^2. The authors stressed the importance of preferential flow contributing to flow and transport into the tile drains on this specific site. Some key factors of this experiment are summarized in Table 3.

Table 3: Some data pertinent to the field experiment on PPP concentration monitoring in subsurface tile drain water reported in Wettstein et al. (2016).

		Application							
substance	**Class**	**type**	**time**	**rate [g/ha]**	**Crop interception [%] [a]**	**DT_{50} [d]**	**K_{Foc} [mL/g]**	**Mass recovery [%] [b]**	**Peak concentration in tile drain water [µg/L]**
Thiamethoxam	Insecticide	Seed dressing	March 19	33.4	0	31	68	1.2	2.83
Imidacloprid	Insecticide	Seed dressing	March 19	50	0	71	225	0.48	1.29
S-Metolachlor	Herbicide	Spray	March 21	450	0	30	189	0.032	0.712
Kresoxim-methyl	Fungicide	Spray	July 17	125	0.2 / 0.7	0.87	308	0.003	0.090
Kresoxim-methyl acid	Metabolite	Formation in soil	–	119.4 [c]	0.2 / 0.7	8.8	23	0.17	2.98
Epoxiconazole	Fungicide	Spray	July 17	225	0.2 / 0.7	226	1073	0.013	0.35

[a] The application rate to the soil is corrected for the (estimated) crop interception

[b] Total loss in the field (= mass recovery) is defined as the mass of substance detected in the tile drains per unit area normalised by the mass of the substance applied per unit area. The drainage relevant surface area was $1040m^2$ in the field study.

[c] The application rate of the metabolite kresoxim-methyl acid was calculated using application rate of the parent compound kresoxim-methyl, a worst case formation fraction of 1, and the molecular weights of both substances.

Precipitation and drainage discharge are shown in Figure 11 for the early spring application. The insecticides and the herbicide were applied before the rainfall event of March 22. Spring 2014 was dry, so that the rainfall events of March 22–23 and April 5–8 hardly generated any drainage discharge. Nevertheless, all applied PPPs were detected in the drainage water in low concentrations of 26ng/L at most. Even the start of a longer period with rainfall on April 25 did hardly generate any drainage discharge, not until the storm event (17.2mm) on April 30. Highest concentrations were measured for all PPPs in the drainage water during this storm event.

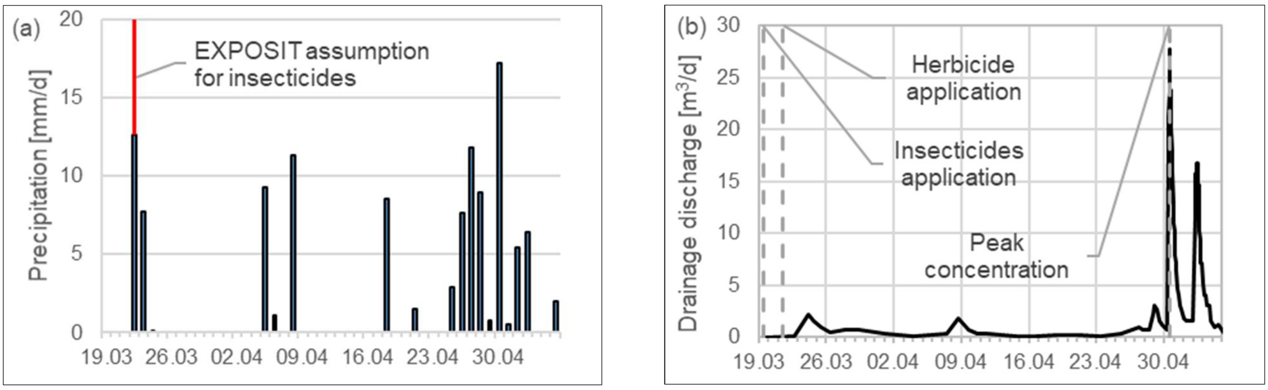

Figure 11: Precipitation (left) and drainage discharge (right) for the early spring application of the insecticides thiamethoxam and imidacloprid (March 19) and the herbicide S-metolachlor (March 21) in the field experiment on PPP concentration monitoring in subsurface tile drain water reported in Wettstein et al. (2016). The storm event of the EXPOSIT model, three days after the application of the insecticides, is shown in red (not shown for S-metolachlor, which would occur two days later).

The situation was different for the summer application of the fungicides on July 17 (see Figure 12). Precipitation amounted 160mm between June 23 and July 14, so that the soil was wet at the time of application. A 3-days period with heavy rainfall started on July 20, i.e. three days after the application. The peak in the drainage discharge, coinciding with the peak concentrations, followed a storm event of 6 mm in one hour (between 20:00 and 21:00 hour on July 22). Note also the much higher drainage discharge rates in the summer compared to early spring.

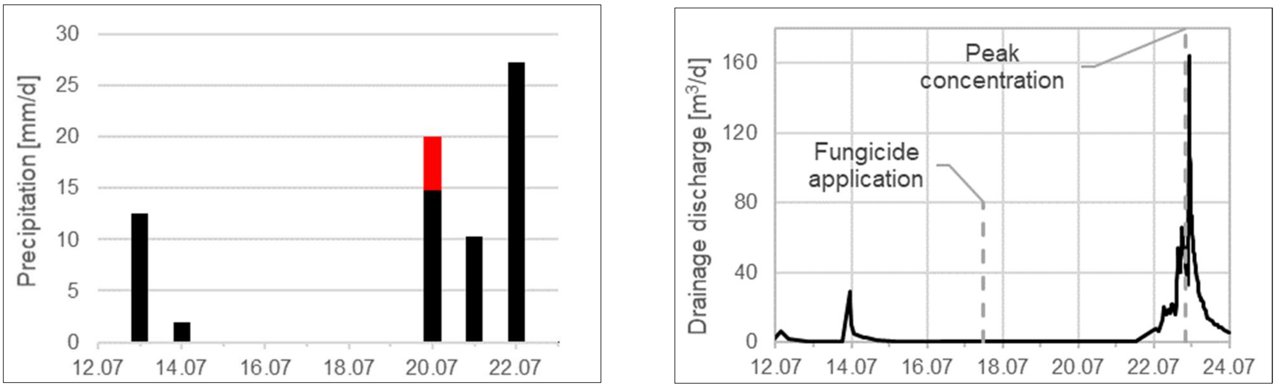

Figure 12: Precipitation (left) and drainage discharge (right) for the summer application of the fungicides epoxyconazole and kresoxim-methyl (July 17) in the field experiment on PPP concentration monitoring in subsurface tile drain water reported in Wettstein et al. (2016). The storm event of the EXPOSIT model, three days after the application of the fungicides, is shown in red.

To conclude, the early spring applications did not reflect the worst-case model assumptions considering the meteorological conditions, because the soil was too dry and the heavy rainfall event triggering the peak concentration occurred only about 40 days after the applications (three days in EXPOSIT). On the other hand, the summer application matched the worst-case model assumptions fairly well.

2.6.3 Total loss

Total loss in the field (= mass recovery) is defined as the mass of substance detected in the tile drains per unit area normalised by the mass of the substance applied per unit area. The drainage relevant surface area was 1040m^2 in the field study. Total loss in EXPOSIT is defined as the mass of substance detected in the tile drains per unit area normalised by soil residues at the time of the heavy rainfall event (tref = 3 days) per unit area, except for metabolites (tref = 0). Note that the application rate in the model was corrected for the crop interception at the time of application. The drained agricultural field has an area of 1ha. Thus, total losses predicted by EXPOSIT do not reflect total losses found in the field, because of the differences in reference time and the normalisation of the mass losses.

However, total loss predicted by the model can be re-calculated to match the field data, but this introduces some uncertainty. To correct for the difference in reference time, degradation half-life values are needed. In the field experiment, soil-specific degradation half-life values have not been measured for the target substances. In the regulatory context, where EXPOSIT is used, half-life values are measured in at least four soils with contrasting properties for active ingredients. Thus, the geometric mean of half-life values is available for the target substances, which were listed in Wettstein et al. (2016). These values were used to re-calculate the loss factor in EXPOSIT based on the application rate at t = 0.

The application rate of thiamethoxam and imidacloprid as seed treatments and S-metolachlor as a pre-emergence herbicide was not affected by crop growth, i.e., the crop interception is 0, but the fungicides are applied on the crop. However, the phenological development stage of the sugar beets, expressed as a BBCH-stage (typically used to identify the phenological development stages of plants), at the time of the fungicide application itself was not documented in Wettstein et al. (2016), other than that BBCH-stage 39 was reached on August 8, i.e., after the fungicide application on July 17. In the regulatory context, crop interception as a function of BBCH-stage is specified for several crops in EFSA (2014). Sugar beets, for example, have a crop interception of 20% for BBCH-stages 10–19, 70% for stages 20–39, and 90% for stages 40–89. Thus, the crop interception at the time of the fungicide application was somewhere between 20 and 70%. Total loss from EXPOSIT is re-calculated based on the non-corrected (i.e., no correction for crop interception) application rates. The total losses are summarized in Table 4 and are shown in Figure 13.

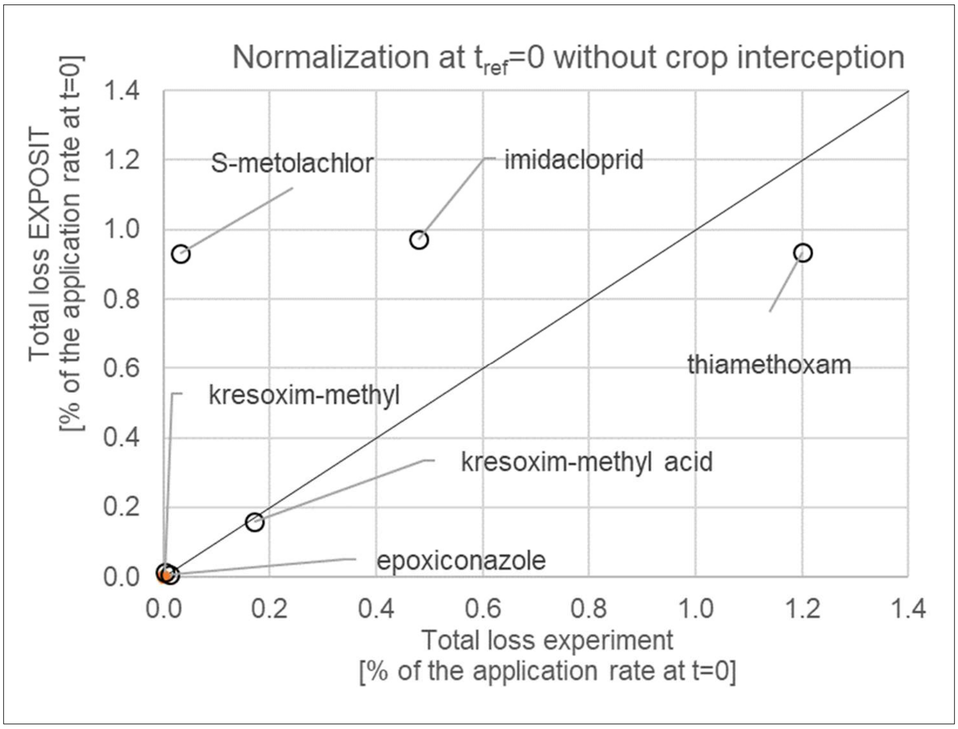

Figure 13: Comparison of total losses in the field experiment of Wettstein et al. (2016) and as predicted by EXPOSIT. The model values were re-calculated based on the time of application (t_{ref} = 0, without degradation) and the application rate (without crop interception) to be able to make the comparison with field measures. Crop interception for the fungicide application was assumed to be 20%.

Table 4: Total loss in the field experiment and calculated by EXPOSIT.

			FIELD	**EXPOSIT**		
Substance	**Mobility class**	**Season**	**t_{ref} = 0 d**	**Total loss [%] model output for t_{ref} = 3 d**	**Total loss [%] , application rate re-calculated without CI at t_{ref} = 0 d**	
					20% CI	**70% CI**
Thiamethoxam	K_{oc} < 500mL/g	autumn / winter	1.2	1	0.94	
Imidacloprid	K_{oc} < 500mL/g	autumn / winter	0.48	1	0.97	
S-Metolachlor	K_{oc} < 500mL/g	autumn / winter	0.032	1	0.93	
Kresoxim-methyl	K_{oc} < 500mL/g	spring / summer	0.003	0.2	0.015	0.005
Kresoxim-methyl acid	K_{oc} < 500mL/g	spring / summer	0.17	0.2	0.16	0.060
Epoxiconazole	K_{oc} >> 500mL/g	spring / summer	0.013	0.01	0.008	0.003

CI = crop interception for the fungicide application only, with 20% for BBCH-stages 10–19 and 70% for the stage 20–39 according to EFSA (2017).

2.6.4 Peak concentration

The peak concentration in the ditch is also known as the initial predicted environmental concentration in the ditch and is used in the ecotoxicological risk assessment. However, concentrations were measured in the tile drain water and not in the ditch.

Therefore, we used the percentages of the total loss defined in EXPOSIT, i.e., 12.5% for spring / summer and 25% for autumn / winter applications, to calculate the mass of the substance in the drainage volumes (10m^3 for spring / summer and 100m^3 for autumn / winter application) to get an estimate of the concentration in the tile drain water. The measured and predicted peak concentrations in the drainage water are summarized in Table 5 and are shown in Figure 14. Note that the initial predicted environmental concentrations in the ditch (PECini,ditch) were a factor 2.6 and 8 lower than the concentrations in the tile drains for the autumn / winter applications and the spring / summer applications, respectively, due to dilution in a water conducting (flowing) ditch.

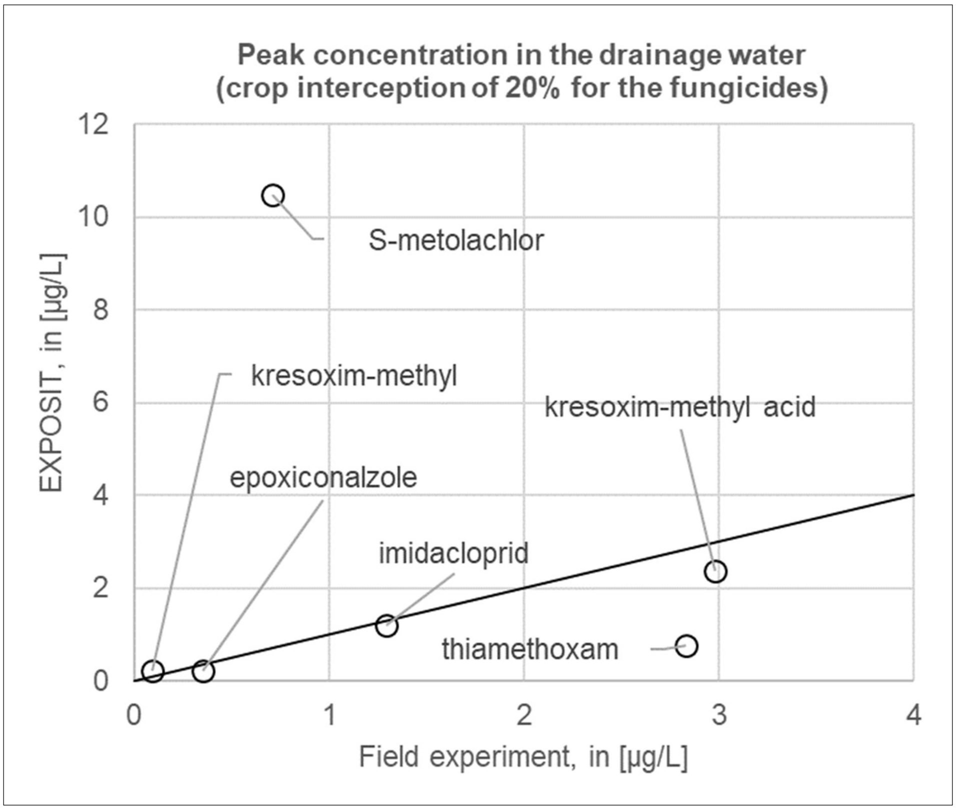

Figure 14: Comparison of the peak concentration in the drainage water in the field experiment of Wettstein et al. (2016) and as predicted by EXPOSIT. The model values were calculated based on model-defined percentages of the total loss (12.5% for the spring / summer applications and 25% for the autumn / winter applications) to be able to compare it with field measures. Crop interception for the fungicide application was assumed to be 20%.

Table 5: Peak concentrations found in the field experiment of Wettstein et al. (2016) and calculated by EXPOSIT based on the percentages of the total loss for spring / summer (12.5%) and autumn / winter (25%) applications.

Substance	**Mobility class**	**Season**	**MEC in tile drain water [µg/L]**	**Days after application**	**Drainage volume [m^3]**	**PEC in tile drain water [µg/L]**		**PEC / MEC**	
						20% CI	**70% CI**	**20% CI**	**70% CI**
Thiamethoxam	K_{oc} < 500mL/g	autumn / winter	2.83	42	100	0.78		0.28	
Imidacloprid	K_{oc} < 500mL/g	autumn / winter	1.29	42	100	1.21		0.94	
S-Metolachlor	K_{oc} < 500mL/g	autumn / winter	0.712	40	100	10.5		14.7	
Kresoxim-methyl	K_{oc} < 500mL/g	spring / summer	0.090	5	10	0.234	0.078	2.60	0.87
Kresoxim-methyl acid	K_{oc} < 500mL/g	spring / summer	2.98	5	10	2.39	0.896	0.80	0.30
Epoxiconazole	K_{oc} >> 500mL/g	spring / summer	0.35	5	10	0.23	0.084	0.64	0.24

CI = crop interception for the fungicide application only, with 20% for BBCH-stages 10–19 and 70% for the stage 20–39 according to EFSA (2017).

PEC = Predicted Environmental Concentration; MEC = Measured Environmental Concentration

2.6.5 Discussion

The role of soil type together with its intrinsic hydraulic properties on the soil water balance is not explicitly accounted for in EXPOSIT, but the assumption of preferential flow as main driver for flow and transport towards tile drains is implicitly included in the loss factors. Preferential flow was also an important phenomenon in Wettstein et al. (2016).

Meteorological data suggests that the experimental conditions at the field site do not necessarily comply with the worst-case assumptions in EXPOSIT, especially for the early spring applications, with the soil being rather dry at the time of application. Nevertheless, EXPOSIT does predict realistic total losses and peak concentrations in the tile drain water for the study of Wettstein et al. (2016) within the same order of magnitude, although measured concentrations (=MEC) are generally larger than predicted environmental concentrations (=PEC; see PEC/MEC ratio in Table 5), with the exception of S-metolachlor. The measured total loss and the peak concentration after a spray application of the herbicide was much lower than predicted. The reason might be that the peak concentration in the tile drains occurred not until 40 days after application in contrast to the default of three days in EXPOSIT, thus allowing more time for degradation in the field. The seed dressing treatment, on the other hand, was apparently not affected by the prolonged time for degradation in the soil before the heavy rainfall event triggered the peak drainage discharge. Thus, the comparison of field data and model predictions suggests that EXPOSIT does yield realistic but not worst case estimates for Swiss conditions, because the meteorological conditions especially in early spring were not worst case.

The loss factors were not deduced specifically for climatic conditions in Switzerland. In the model, the drainage event was initiated by a 20mm rainfall event, including a rainfall intensity of 9mm during 15 min, which has a frequency of occurrence once a year in Germany, which might not fit for Switzerland. Since summer thunderstorms are more frequent in Switzerland, they may also contribute more to drainage flow and may lead to higher drainage peaks.

Another characteristic of the field experiment in Wettstein et al. (2016) was that the cropped field did not cover the entire drained area, causing a time-variable dilution of the concentrations of the target substances in the tile drains. This dilution was estimated to be a factor of 3 at most. Furthermore, it would have been beneficial to know the crop interception of the sugar beets at the time of application of the fungicides.

The peak concentration in EXPOSIT is based on a one-day averaging period. The drainage water samples, however, were collected proportional to the flow rate in the field. The peak concentration of the insecticides and the herbicide was measured in a water sample that was collected during 2 hours and 12 minutes. For a collection period of approximately 1 day (30.04.2014 at 12:38 pm – 01.05.2014 at 10:12 am) consisting of 5 subsamples, the concentration in the tile drain water was 1.04, 0.53 and 0.28µg/L for thiamethoxam, imidacloprid and S-metolachlor, respectively, which is a reduction of a factor of about 2.5 compared to the peak concentration in one subsample. The peak concentration of the fungicides was measured in a sample that was collected during 53 minutes. For a collection period of approximately 1 day (22.07.2014 at 11:50 am – 23.07.2014 at 09:26 am) consisting of 19 subsamples, the concentration in the tile drain water was 0.037, 0.42, and 0.0098µg/L for epoxiconazole, kresoxim-methyl acid, and kresoxim-methyl, respectively, which is a reduction of a factor of about 10, 7, and 9, respectively, compared to the peak concentration in one subsample.

If tile drain water would have been collected for a 1-day period in the field experiment, and thus matching the model requirement, the peak concentrations of the target substance decreased by a factor of 2.5 to 10 times depending on the substance and the time of application. Note that this does not imply that the experimental discharge rates are substantially higher than assumed in EXPOSIT, but reflects the effect of the time window of averaging. In EXPOSIT, a 20mm rainfall event within one day trigger the peak concentration and includes a 9mm storm event with a duration of 15 minutes. With a higher time resolution, peak concentration would also have been larger in EXPOSIT. This illustrates the importance of the time window for sampling when comparing model predictions with experimental measurements.

Wettstein et al. (2016) measured the concentration of the tile drain water, whereas EXPOSIT assesses the initial predicted environmental concentration in the ditch. This measure is used in ecotoxicological risk assessment. The dilution in the standing ditch is a factor of 1.3 and 4 for the autumn / winter application and the spring / summer application, respectively, based on the given drainage volume and the geometry of the ditch. The water in the ditch is assumed to flow, resulting in an additional dilution of the concentration in the ditch. The model uses a constant factor of two, independent of the hydrological conditions, i.e. the inflowing water volume per unit time. No justification or interpretation is given for this factor of two, pinpointing the necessity of research on the mixing behaviour of drainage inputs and its dilution in ditches.

2.6.6 Summary and Conclusion

We have compared total losses and peak concentrations for six substances measured in the tile drain water at an experimental site in Switzerland and compared them with predictions by the model EXPOSIT. We have highlighted issues that complicate the direct comparison of the model prediction and the field measurement for total losses and peak concentrations, such as

(i) the difference in the reference time (t = 0 or t = 3 days) and in application rate (with and without correction for the crop interception),
(ii) the absence of site-specific half-life values for the target substances and the unknown crop interception at the time of the fungicide application,
(iii) the dilution of the concentration in the tile drain water by non-contaminated water from areas that were not covered by the sugar beets,
(iv) the mismatch in sampling time, because of the flow proportional sampling scheme, and
(v) the climatic conditions between Germany and Switzerland may differ, affecting the factors of total loss.

Nevertheless, both the total loss and the peak concentration in the drainage water are in the same order of magnitude in the model and the experiment, with the exception of S-metolachlor having much lower measured than predicted total losses and peak concentration. The meteorological conditions during the experiment were rather dry in spring (not worst case). Moreover, the measured concentrations were in most cases somewhat higher than the predicted concentrations. This suggest that EXPOSIT yields concentrations in tile drain water that are realistic for the field site at Zürich-Reckenholz, but may not be worst case estimates for Swiss conditions.

However, no general conclusions can be drawn regarding the protection level of the exposure assessment, since the measurements covered only one site, which was exposed to local weather conditions of only one year. For example, the rainfall event that triggered a major drainage event that included the peak concentration occurred about 40 days after the application in March, which may explain the lower experimental loss due to degradation for the spray application of S-metolachlor.

Finally, no concentration measurements were performed in the ditch, so that the mixing and dilution behaviour of the inputs from the tile drains into the ditch could not be addressed.

2.7 Existing decision trees to assess the potential for preferential flow

In the following, we discuss which indicators already exist to assess the potential of preferential flow, and whether they can be applied to assess the risk of PPP losses via drainage. We also assess how suited they are to Swiss conditions.

Many pollution indices have been developed for phosphorus (i.e. Gburek et al., 2000; Sharpley et al., 2003), which can be used as proxy for losses of PPP. In Andersen and Kronvang (2006), the initial Phosphorus index (P index) developed for Pennsylvania proved to be too oriented towards big losses and most fields in Denmark were classified as “no risk” or “low risk”. This is a potential issue when using indices developed in regions that have different topography, soils, climate or agricultural practices. The contamination pathways are also particularly different between both regions. In Pennsylvania, there is high surface runoff and erosion risk, whereas in Denmark tile drains are an important pathway because of the flatter topography. The Pennsylvanian index, however, does include a specific parameter for the drainage pathway.

Several P indices mention tile drains, but most account for either the reduction in surface runoff or the enhanced transport through tiles rather than both simultaneously. Reid et al. (2012) provide a summary of the current state of how P indices accounted for tile drainage, and discussed the challenges in predicting the risk of P losses through tile drains that are relative to actual losses.

Regarding pesticide losses, many risk indicators have been presented (Verro et al., 2002; Kookana et al., 2005; Lindahl and Bockstaller, 2012; Macary et al., 2014; Kudsk et al., 2018), but few integrate drainage losses through preferential flow as a loss pathway (Strassemeyer et al., 2017).

2.7.1 GUS index (Groundwater Ubiquity Score)

The GUS index (Groundwater Ubiquity Score) was initially proposed by Gustafson (1989). It combines the adsorption strength (K_{oc}) and the degradation constant DT_{50} of compounds. He distinguished two classes: “leachable” and “non-leachable”. Later research has shown that this distinction was a bit too simple when macropore flow becomes important (Kördel et al., 2008).

The FOOTPRINT project (Dubus et al., 2009), Jarvis et al. (2009), Jarvis et al. (2012) and finally the TOPPS (TOPPS, 2018) working group have come up with risk indicators that can be applied to assess the risk of PPP losses via drainage. They are reasonably well adapted to Swiss conditions, although the application of those decision trees results in too little variability to allow differentiating between more than two classes of risk. We briefly present the approaches described in the FOOTPRINT project and by subsequent works of Jarvis (Jarvis et al., 2009 and 2012) in the following sections.

2.7.2 FOOTPRINT

The FOOTPRINT project (Dubus et al., 2009) was a European project that developed various methodologies to quantify the risk of PPP losses via leaching and tile drainage. They suggested the decision trees in Figure 15 for both topsoil and subsoil horizons, resulting in three and four classes of risk, respectively. The risk level 1 is the lowest considered in those decision trees. Soil horizons are described as follows (based on Jahn et al., 2006):

- O: Organic surface layer composed of a litter of relatively undecomposed plant residues
- A: Surface soil composed of a layer of mineral soil with most organic matter accumulation and soil life
- B: Subsoil layer, usually less rich in organic matter than the A horizon, which may accumulate iron oxides and clay minerals as a result of weathering
- C: Substrate layer of poorly-weathered rock
- E: Can be a mineral master horizon that presents some loss of Fe, Al, clay, or organic matter.
- H: Horizon dominated by organic material (undecomposed or partially decomposed), which may be underwater. All H horizons are saturated with water for prolonged periods, or were once saturated but are now drained artificially.

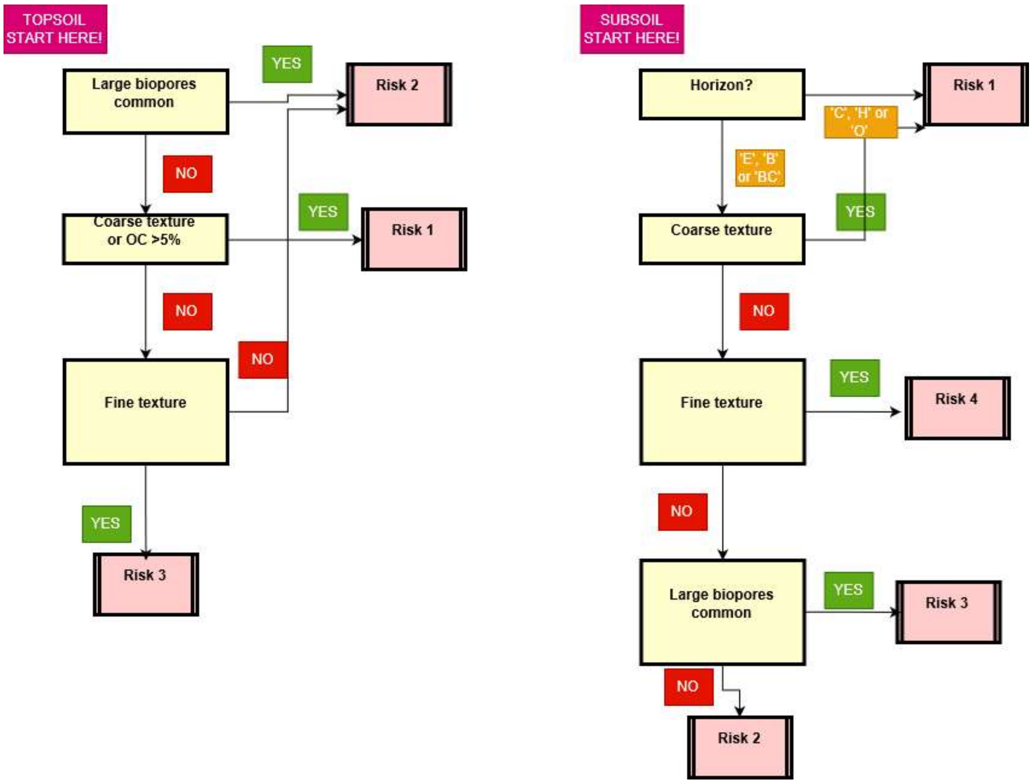

Figure 15: Flowchart of the FOOTPRINT approach to classify soil horizons with respect to the strength of macropore flow (based on Dubus et al., 2009).

In the FOOTPRINT method as well as the decision trees by Jarvis et al. (2009) shown in the next section, the soil texture properties (fine / medium / coarse) are defined based on the USDA soil texture triangle as shown in Figure 16.

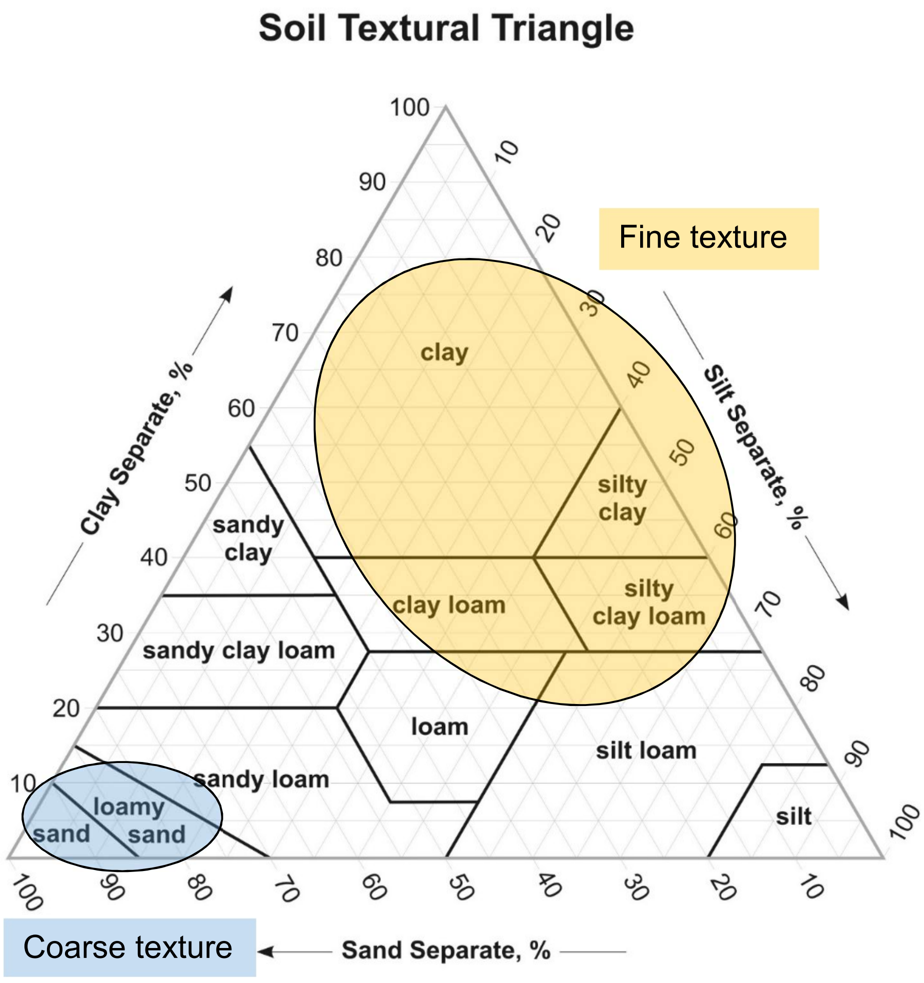

Figure 16: USDA Soil textural triangle with fine and coarse groups as specified by the footprint methodology (USDA, 2020).

Coarse texture: *sand or loamy sand; fine texture: clay, silty clay, clay loam, or silty clay loam according to the USDA system.*

We refer the reader to the appendix 3.7.9 of the Swiss soil classification report (BGS, 2010) for an illustration of the Swiss soil texture triangle. It is slightly different from the rather widely used USDA soil triangle.

2.7.3 Jarvis et al., 2009

Jarvis et al. (2009) built upon the FOOTPRINT approach to propose a more complex set of decision trees as shown in Figures 17 and 18. Moeys et al. (2012) summarize the approach as follows: *"The susceptibility to macropore flow of each horizon is determined with a decision tree, described in detail and successfully tested by Jarvis et al. (2009). The decision tree is based on USDA soil textural classes, FAO Master Horizon designations, tillage characteristics (no or reduced tillage, conventional tillage/ploughing or harrowing) and organic carbon content. The decision tree also makes use of a subsidiary decision tree to predict the abundance of large earthworm biopores (Lindahl et al. (2009) from soil climate, land use, texture class and the presence of limiting factors (such as horizons without pedogenetic features or with coarse texture, water tables, low pH and high bulk density)."*

For each susceptibility class, they associated parameter values for the MACRO model according to expert judgement based on extensive experience from calibrating and validating the model against experimental data (i.e. Jarvis, 2007; Köhne et al., 2009a, b).

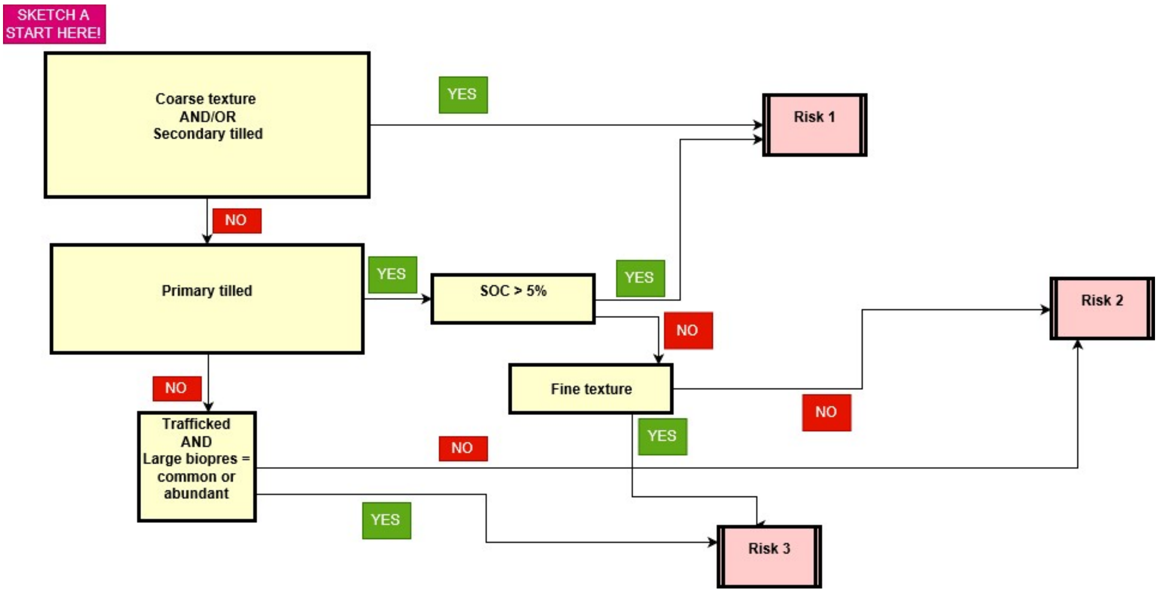

Figure 17: Flowchart to assess the susceptibility to macropore flow in topsoil (based on Jarvis et al., 2009).

Primary tillage refers to plowing, while secondary tillage refers to more intensive operations using implements that destroy the soil structure (harrows and rotovators).

The model classifies each soil horizon into four susceptibility classes for macropore flow. Figure 17 deals specifically with the topsoil horizon whereas Figure 18 can then be applied to every subsoil horizon.

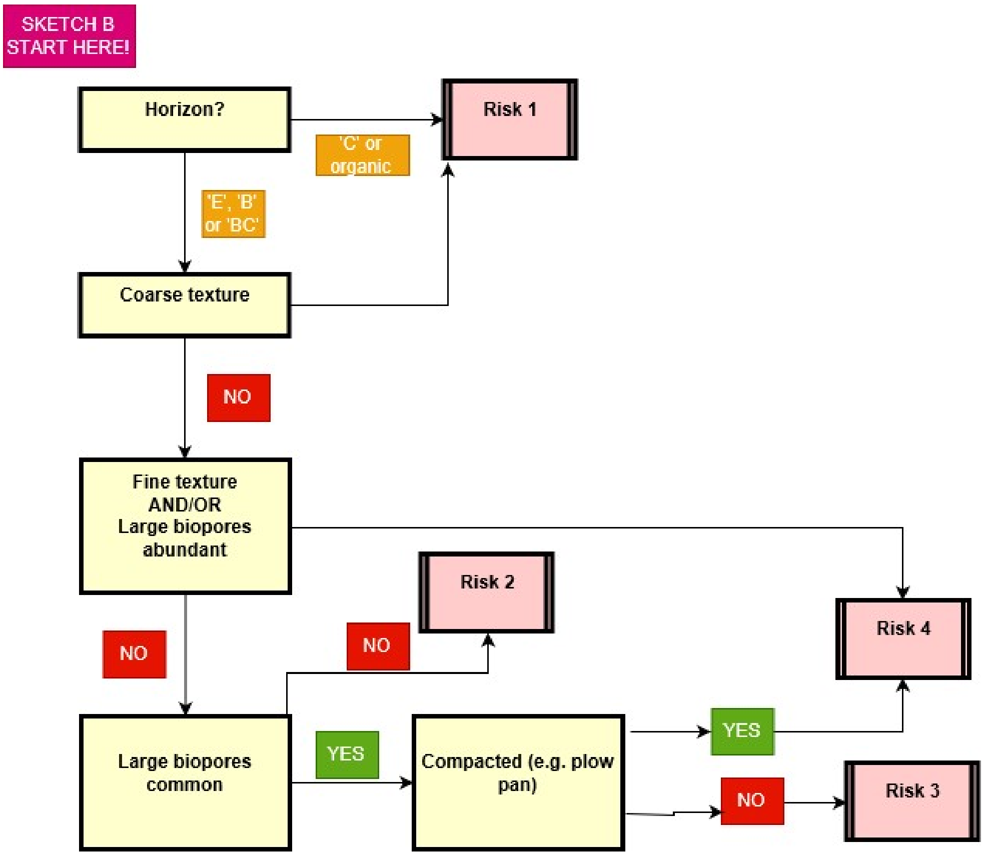

Figure 18: Flowchart to assess the susceptibility to macropore flow in the individual subsoil horizons (based on Jarvis et al., 2009).

Whether large biopores are common or not is assessed based on the following flowchart (Figure 19) suggested by Lindahl et al. (2009) and further adapted by Jarvis et al. (2009). The decision tree starts with a question regarding the type of soil climate. We have kept the exact decision tree suggested in Lindhal et al. (2009), although none of those climates applies to the agricultural soils in Switzerland. As defined in Jahn et al. (2006) and IUSS (2006), a soil with aridic (from "dry") properties combines a number of properties that are common in surface horizons of soils occurring under arid conditions and where soil formation exceeds accumulation at the soil surface by aeolian or alluvial activity. Torric properties are similar, meaning hot and dry. A pergelic soil is a perennially frozen soil (permafrost), whereas a cryic soil is very cold but does not have permafrost.

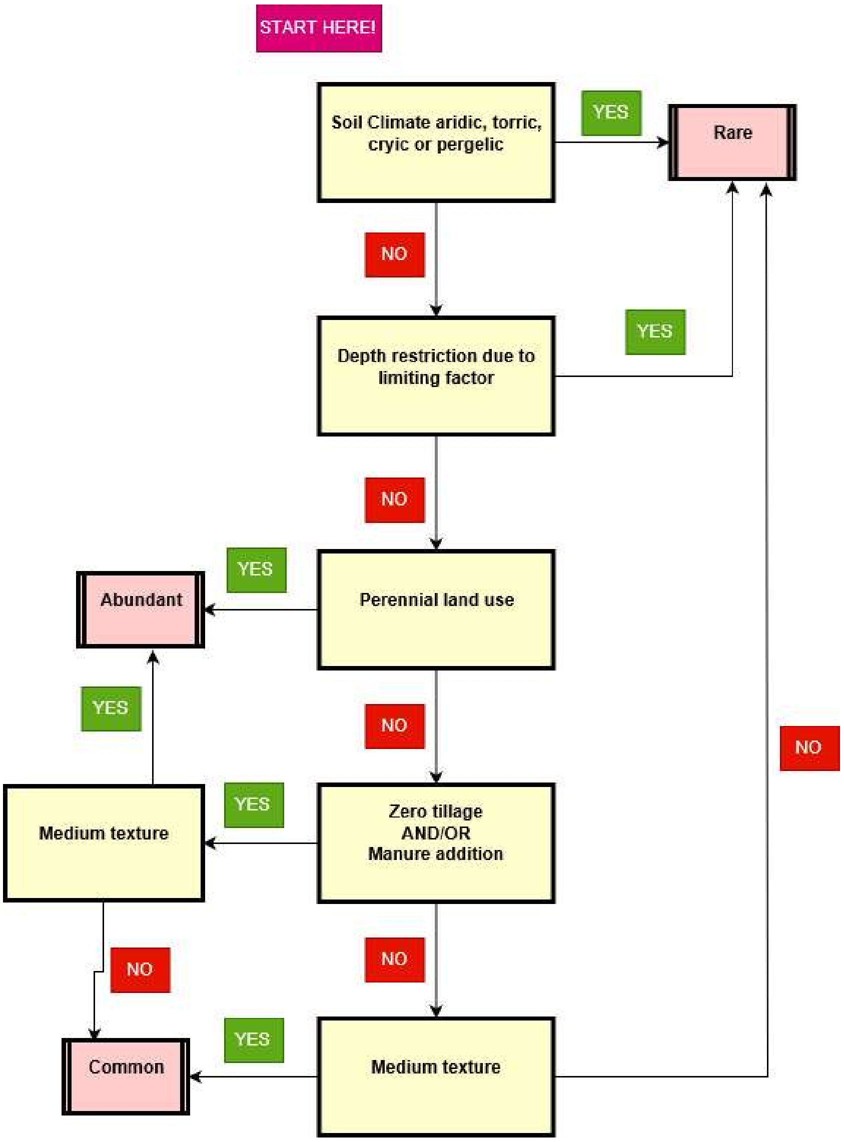

Figure 19: Abundance of earthworms based on Lindahl et al. (2009) and Jarvis et al. (2009).

For definition of aridic, torric, cryic and pergelic, see IUSS (2006) and Jahn et al. (2006). Coarse texture: sand or loamy sand according to the USDA system.

2.7.4 Jarvis et al., 2012

Jarvis et al. (2012) further integrated the three previous flowcharts (Fig. 17, 18 and 19) into a single decision tree illustrated in Figure 20 and described the approach as follows: *"Jarvis et al. (2009) described a classification scheme designed to support spatial model predictions of pesticide losses to surface water and groundwater, which is more ambitious and generic in scope. The scheme, which takes the form of a simple* *decision tree, was derived from a combination of simple ‘rules of thumb’ derived from a review of the literature (Jarvis, 2007) and statistical analyses of factors influencing soil aggregation and the abundance of anecic earthworms (Lindahl et al., 2009).”*

Figure 20 starts with a question regarding “andic” or “vitric” properties of the soil horizon. We have kept the exact decision tree suggested by Jarvis et al. (2012), although agricultural soils in Switzerland do not exhibit those properties. A soil horizon, which has andic properties, results from moderate weathering of mainly pyroclastic deposits. Vitric properties apply to layers with volcanic glass and other primary minerals derived from volcanic eruptions. For more details, see IUSS (2006).

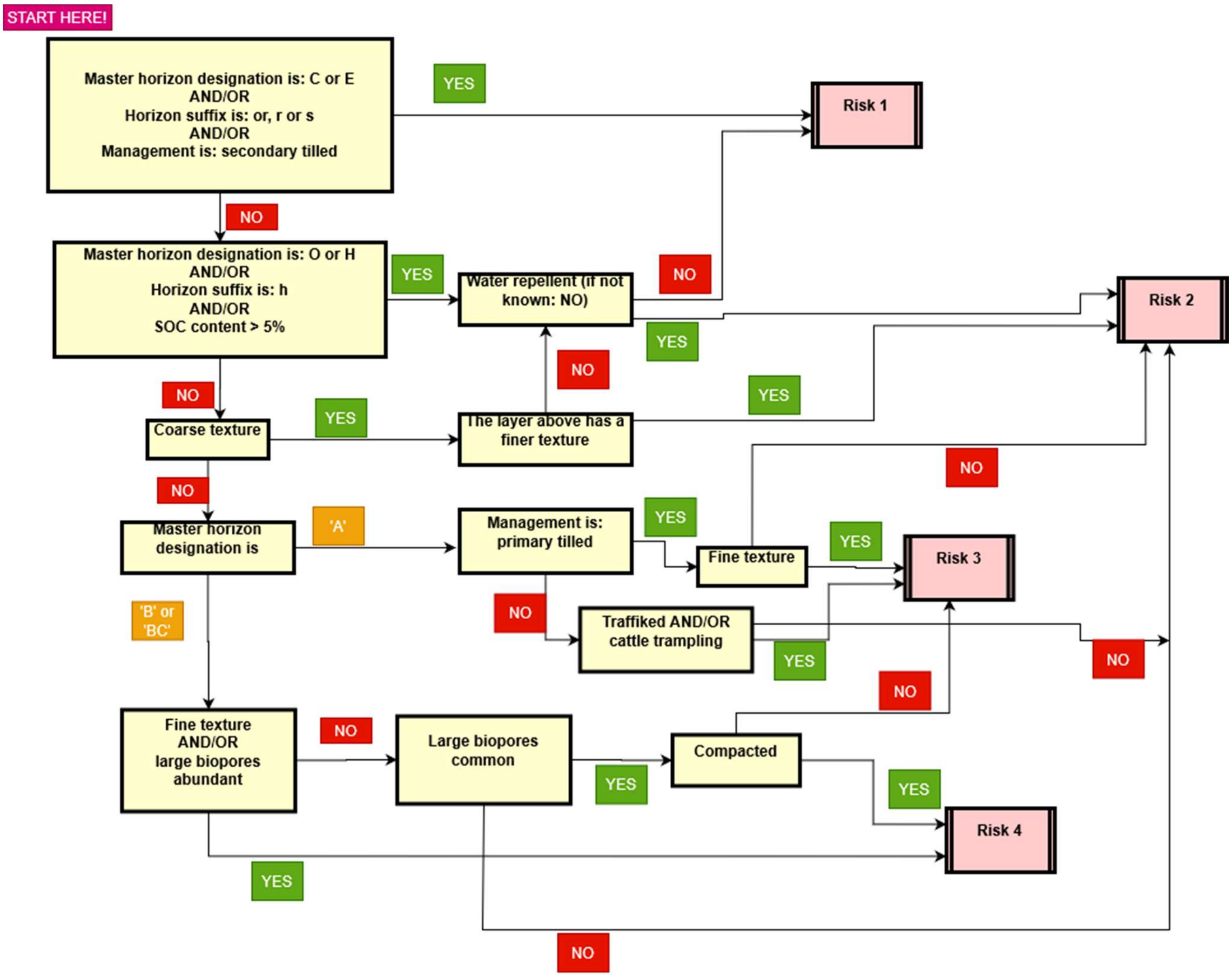

Figure 20: Decision tree to support predictions of the effects of preferential flow, based Jarvis et al. (2012).

For definition of Andic/Vitric material, as well as master horizon types and horizon suffixes, see IUSS (2006). Coarse texture: sand or loamy sand; fine texture: clay, silty clay, clay loam, or silty clay loam according to the USDA system. Primary tillage refers to plowing, while secondary tillage refers to more intensive operations using implements that pulverize the soil (harrows and rotovators). Classes I, II, III, and IV imply ‘negligible’, ‘low’ ‘moderate,’ and ‘high’ impact of preferential flow in terms of accelerating flow/transport velocities through the horizon. Referring to the classification by Weiler and Flühler (2004), class I can be equated with homogeneous flow, class II with heterogeneous flow or weak macropore flow, and classes III and IV with moderate and strong macropore flow, respectively.

However, the focus of Jarvis et al. (2012) is on the potential for preferential flow in soils and not the potential for pesticide losses. They therefore concentrate on the properties of soil horizons and not on the general properties of an agricultural site. In the field, PPP losses will be influenced by more general aspects such as the potential of surface runoff onto drained areas originating from nearby slopes, or specific local groundwater dynamics.

Overall, the decision trees have a wide category for medium textured soils. A distinction could be made for silty soils that are prone to developing crusts, which limit surface infiltration. Those soils are only found in the North-West part of Switzerland, for example in the Leimental catchment in canton Basel-Landschaft (Konz and Lang, 2018).

Most soils in Switzerland, however, fall in the medium textural category. This leads to a medium risk related to pesticide contamination through preferential flow. Those decision trees however do only take into account site properties nor climate. Pesticide transport being strongly driven by meteorological parameters, such as the time between application and the first heavy rain event; the risk of drainage losses is therefore highly dynamic throughout the season. Climate statistics, such as mean duration between storm events, typical storm intensity and total storm rainfall, could be added to better define the risk at a specific location.

2.7.5 TOPPS, 2018

The TOPPS Prowadis working group ("Train Operators to Promote best management Practices & Sustainability"; TOPPS, 2018) developed a decision tree for drainage losses and another for leaching losses to groundwater. We present here in Table 6 the first decision tree focusing on drainage losses. The depth / water holding capacity of the soil profile is particularly important if matrix flow is prevalent. The TOPPS decision tree includes this variable when tile drains are installed to control shallow groundwater. If the unsaturated zone is shallow and/or has very little water holding capacity, then PPP losses will be high as adsorption and microbial degradation will be limited due to short residence times. The water-holding capacity used here is equivalent to the field capacity, which is the water stored in soil and not lost by gravity a few days after soil saturation. The TOPPS decision tree also differentiates peaty soils due to their very high soil organic carbon content. We refer to those organic soils in the next section (2.8 Conceptual model).

Table 6: Decision dashboard for losses to drainage from the TOPPS workgroup (TOPPS, 2018).

Drainage due to low-permeability soil	Large cracks/macropores occur			High risk
	Large cracks/macropores do not occur in most years	Subsoiling or moling done		High risk
		No subsoiling or moling done	Clay > 35%	High risk
			Clay 25 to 35%	Medium risk
			Clay < 25%	Low risk
Drainage to control shallow groundwater	Mineral soil	Large cracks/macropores occur		High risk
		Large cracks/macropores do not	WHC < 150mm	High risk
			WHC 150-230mm	Medium risk
			WHC > 230mm	Low risk
	Peaty soil			Low risk

Large cracks / macropores occur when they are visible and >1cm at the soil surface. Peaty soils are soils with >30% Soil Organic Matter (SOM) in topsoil. WHC is the soil water-holding capacity at field capacity in the upper 100cm of the soil profile or above the level of the drains, whichever is shallower.

Most Swiss soils fall into the medium risk category. The question therefore arises whether this approach can be further refined or whether other factors, such as the weather conditions, should be integrated in the risk assessment approach. A large percentage of the Swiss cultivated soils are loamy luvisols /cambisols. The clay content is usually less than 35%. We think the additional parameters that have the largest impact in Switzerland are weather conditions, catchment properties and agricultural practices. These factors are discussed in the next section, which presents a summary of the aspects presented so far in the form of a conceptual model.

2.8 Conceptual model on key processes affecting PPP losses to drainage

2.8.1 Impact of key parameters on PPP losses

Table 7 presents a literature-based assessment of the influence of various parameters on the risk of PPP losses via drainage. The parameters are grouped into categories such as drainage properties, climate, soil, catchment properties, PPP properties, crops and agricultural practices.

Parameters highlighted in blue are quite constant place-related parameters. Those highlighted in orange are more easily affected by agronomic and / or management changes. The orange parameters are thus most suited for direct mitigation measures at the farm-scale, whereas the blue parameters involve more technical measures, such as artificial wetlands or drainage re-designs.

Table 7: Effect of key parameters on PPP losses via drainage (focus on peak concentration).

Category	Parameter (analyzed as increasing in value)	---	--	-	0	+	++	+++	Uncertainty
Drainage	Depth of subsurface drain	x	x						x
Drainage	Drain spacing		x	x					x
Drainage	Drain condition			x	x				x
Drainage	Improved drainage (permeable filter, i.e. gravel)					x	x		xxx
Climate	Total winter precipitation				x	x	x		xx
Climate	Total summer precipitation				x	x	x		xx
Climate	Total yearly precipitation				x	x			xx
Climate	Mean summer temperature			x	x				xx
Climate	Mean winter temperature			x	x	x			xxx
Soil	Clay content						x	x	x
Soil	Silt content			x	x	x	x		x
Soil	Sand content			x	x				x
Soil	SOC content	x	x						x
Soil	Water holding capacity		x	x					x
Soil	Saturated hydraulic conductivity			x	x				xx
Catchment properties	Slope		x	x	x				xx
Catchment properties	Runoff from nearby slopes			x	x	x	x		x
Catchment properties	Ratio of critical source areas for infiltration / runoff					x	x	x	x
PPP properties	DT_{50}						x	x	x
PPP properties	K_{OC}		x	x	x				xx
PPP properties	Volatility		x	x					x
Crops	Temporary grassland	x							x
Crops	Winter rapeseed and winter cereals		x	x					xxx
Crops	Sugar beet, maize					x	x		xxx
Crops	Vegetable and potatoes						x	x	xxx
Crops	Soil cover		x	x					x
Agri practice	Tillage intensity: conventional			x	x				xxx
Agri practice	Tillage intensity: reduced (mulch, strip)			x	x	x			xxx
Agri practice	Tillage intensity: no-till				x	x	x		xxx
Agri practice / weather	Time between application and first intense rain event	x	x						x
Agri practice / weather	Intensity of first rain event after application						x	x	x
Agri practice / soil	Soil wetness at application date			x	x	x	x	x	xx

"Zero" means that an increasing value of the parameter will have no or little effect on peak PPP losses. "+++" means that an increasing value of the parameter will strongly contribute to higher peak PPP losses (vice-versa for "---"). The parameters are divided into two groups: highlighted in blue are environmental parameters, which cannot be affected in the short-term by mitigation measures. In orange are those that are more readily affected by mitigation measures. The highest impact of some parameters ("+++" or "---") is highlighted in green. The uncertainty denotes the confidence with which the effect of each parameter is assessed based on the literature. The most uncertain parameters are highlighted in red.

Table 7 is suggested with preferential flow in mind. The share between preferential flow and matrix flow reaching drains is quite variable. Matrix flow is however less critical with regard to peak drainage losses as PPPs have more time to degrade, and experience more contact area to sorb onto soil surfaces. However, the bulk mass of PPP may still be located in the matrix and will be transported through the matrix. In a review on transport of pesticides via macropores, Kördel et al. (2008) describe the importance of macropores as well as most parameters in the table. Below, we attempt to explain our reasoning behind the impact of each parameter on losses of PPP via drainage.

Drainage network

PPP losses via drainage will generally end up in the same water bodies as losses from runoff or erosion but, depending on the design of the drainage network, it is not unlikely that the drained catchment becomes different (bigger or smaller) than the natural hydrological catchment.

- Depth of subsurface drain:

With a deeper drain, macropores originating from the surface will be less likely to remain connected. On the other hand, more water can be drained by drainage, as the drained water table will be lower. It will thus lead to lower peak losses but not necessary much lower total losses.

- Drain spacing

Kladivko et al. (2001) noted greatest pesticide losses per area occurring with the smallest spacing (5m) and lowest losses occurring on the 20m spacing. If the groundwater table is below the drain level, a very small surface area may contribute to drain flow as the probability that macropores directly flow into the drain is negligible (see Section 2.3, Figure 6). If the groundwater table is higher than the drain, more lateral subsurface flow paths will extend the surface area contributing to drain flow, leading to a higher drained volume. If the drain is on a slope, a wider area could also be contributing via lateral flow paths (Stamm et al., 2002). In any case, the wider the spacing, the smaller peak losses will be.

- Drain condition

The older the drain, the more likely it will not fully function anymore. This reduces the risk of PPP losses via drainage, but can increase losses via runoff or erosion.

- Improved drainage (permeable filter, i.e. gravel)

Drains are sometimes “improved” by backfilling the trench with gravel or other high hydraulic conductivity materials. This will increase the risk of PPP losses but it will also be very hard to know in which way drains were initially installed.

Climate

- Total winter precipitation

The more winter precipitation, the more active drains will be during winter. This can enhance losses of (persistent) PPPs applied in late autumn for winter cereals, as well as for early spring applications because of saturated soils. This parameter will influence the flow pattern to drains (does the water table reach the drains during winter or spring?) and will therefore be an important factor controlling the total amount of PPPs leached during winter.

- Total summer precipitation

Dry summers will lead to little PPP losses. However, wet summers can lead to activating the drains, especially via preferential flow while wet soils will retain less of the infiltrating water. Lysimeter records suggest that, although there are generally 3 to 4 months where drainages are predominantly inactive (June-September), some wet summers (1–2 in the last 10 years in Switzerland) have led to year-round drainage. Although pre-emergence herbicides and seed-dressings are applied in early spring, most fungicides and insecticides are applied in late spring and summer during the main growing season. Summer rains may therefore generate higher PPP peak concentrations than during winter precipitation.

- Total yearly precipitation

The yearly rainfall mainly has an impact on the total amount of pesticides leached to groundwater and drains. A more important aspect of yearly rainfall is its distribution throughout the year (see item winter and summer precipitation), which controls when and how much drain flow will be generated. Combining the two preceding parameters, a high yearly rainfall results in an increase in total PPP losses via drainage but does not necessary lead to higher peak losses.

- Mean summer temperature

Higher temperatures during the growing season lead to quicker PPP degradation and therefore decreased losses. The impact of higher degradation rates on peak PPP losses is however much more important in combination with the time elapsed before a significant rain event occurs than the time taken for solutes to reach the drains.

- Mean winter temperature

Mean winter temperature accelerates the degradation of PPPs remaining in soil at the end of the growing season. On the other hand, warmer winters also tend to bring more precipitation leading to drains being active longer or more intensely, leading to increased total PPP losses. A warm winter may also lead to earlier sowing and earlier weed development, which would require more intense and/or earlier spring PPP applications. In addition, more winter crops may be sown, increasing the autumn application of pesticides (Lewan et al., 2009). For those reasons, we listed mean winter temperature as having weak effects on PPP losses, especially peak losses. Those effects lead to either a decrease or an increase in losses depending on agricultural conditions.

Furthermore, Bloomfield et al. (2006) present a very comprehensive summary of the impacts of climate change on the fate and behavior of pesticides in surface and groundwater from a UK perspective (see section 4.4 for more details). Lewan et al. (2009) also concluded as follows on the combination of soil moisture and weather conditions leading to high losses: *“The soil water deficit at application and medium-term rainfall (30–90 days after application) were the two most important factors determining pesticide losses predicted following autumn applications. For spring applications, precipitation the following winter (90–180 days and 180–360 days after application) exerted an important control on total pesticide losses to drains and groundwater, while short-term (5-day) precipitation and antecedent soil water deficit were identified as the two most important explanatory variables for maximum pesticide concentrations in drain flow.”*

Soil

- Clay content

Clay content is a key driver in the development of macropores (Koestel and Jorda, 2014). Cracks form upon drying and close upon wetting. On the other hand, a too high clay content will not be favorable for earthworms. They prefer loamy soils in which it is easier to create burrows.

- Silt content

The water holding capacity of silty soils is high, leading to rather low PPP losses. A higher silt content can also lead to surface sealing when bare soil is exposed. An intense precipitation event would then lead to high runoff and erosion losses and consequently less PPP losses via drainage. On the other hand, high silt content is conducive to high earthworm activity and development of biopores. As opposed to clayey soils, bio-macropores do not close in wetter conditions. This leads to potentially higher peak PPP losses via drainage.

- Sand content

Sandy soils will lead to more and quicker matrix flow. A specific type of preferential flow, finger flow, can develop in dry sands but it does not have such a substantial impact on solute transport as preferential flow through macropores.

Because sandy soils mainly transport PPPs via matrix flow and are little prone to generating runoff, their contribution to peak losses should be low (Sandin et al., 2018). On the other hand, adsorption is generally low in sandy soils, so total drained and/or leached chemical fluxes could be higher. There are only few sandy soils in Switzerland, so these aspects are less relevant than in other European countries.

- Soil Organic Carbon (SOC) content

SOC provides adsorption sites for PPPs. Ng et al. (1995) consider SOC as the best single predictor for adsorption. It also helps forming stable soil aggregates, which have the tendency to limit preferential flow while increasing matrix flow (Jarvis, 2007). As SOC tends to increase the infiltration capacity, more matrix flow develops and more organic material can sorb pollutants. A possible impact is a decrease in pesticide leaching / pesticide loss via drainages. High SOC content thus often has a reducing impact of PPP losses. Ng et al. (1995) report that in some high organic carbon soils the movement of herbicide residues may be as much as tenfold less than the rate of water movement. Finally, as mentioned in Section 2.1, the fate of certain classes of PPPs that behave as weak acids will not depend much on SOC content if their pK_a value is in the range of the soil pH.

However, Kördel el al. (2008) stress that more organic matter leads to higher macroporosity as well as more stable macropores, which increase PPP losses by macropore flow to drainage. We should finally keep in mind that the range in SOC content of Swiss arable land is relatively small (within 1–3%), which attenuates the impact of local variations of SOC on PPP losses via drainage. Finally, this parameter may not necessarily have a huge impact of drainage losses if those mainly occur through preferential flow, as adsorption may not have time to occur. On the other hand, if matrix flow prevails, a high SOC content means higher adsorption properties and decreased losses of easily sorbed PPPs.

It is usual in the literature (i.e. TOPPS, 2018) to define organic soils as having more than 30% SOM (18% SOC). They present a specific case because of this much higher content. This high organic matter content leads to very high adsorption capacity. In addition, those soils generally have a high water-holding capacity, which enables more stormwater volume to be stored and more PPP retardation by adsorption. Soils with high organic matter content are therefore less susceptible to drainage losses of PPP. Gramlich et al. (2018), however, note that degraded peaty soils could become more susceptible to erosion. They might also develop voluminous cracks and progressively lose water-holding capacity as they degrade with time (Holden et al., 2006). The microbial activity is often higher in organic soils, but does not necessarily lead to higher degradation rates of PPPs accumulated in the intermediate soils layers. Microbial communities are indeed not necessarily specialized for PPP degradation and may be inhibited by other environmental factors (Castillo and Torstensson, 2007).

- Water holding capacity

The more water can be stored in soil, the more likely solutes will be stored in the matrix for longer periods. More time available for PPP degradation processes may lead to lower losses. On the other hand, the high water holding capacity of loamy soils promotes earthworm activity and abundant plant roots, leading to more macropore flow and higher peak PPP losses to drains. We assessed this second effect as less strong than the trapping of solutes in the matrix, and therefore linked higher water holding capacity to reduced PPP losses.

- Saturated hydraulic conductivity

The higher the soil saturated hydraulic conductivity, the less time PPPs will have to degrade (given the same hydraulic gradient), leading to higher losses for chemicals within a medium range of persistence. The relationship is not quite simple as the unsaturated hydraulic conductivity in soils also depends on soil moisture, especially for sandy soils. Finally, a higher hydraulic conductivity is often correlated with less preferential flow, thereby leading to less PPP losses to drains via preferential flow.

Catchment properties

- Slope

The higher the slope, the higher the ratio runoff / infiltration will be. Losses via drainage will therefore become lower (Gramlich et al., 2018). Koch and Prasuhn (2020) estimated that 72% of drained land may have a slope higher than 2%.

- Runoff from nearby slopes

Runoff from surrounding slopes can accumulate into depressions and lead to a higher amount of infiltrated water than would be expected by looking at each field in isolation. This can locally be quite dramatic (Doppler et al., 2012), but remains an untypical situation in Swiss arable land. This would potentially lead to higher peak losses via drainage. On the other hand, if runoff runs across a drained surface that is not topographically depressed, it will continue its course and may help diluting the applied PPP, thus reducing overall peak losses via drainage.

- Ratio of critical source areas for infiltration / runoff

The more infiltration areas in a catchment, the higher this ratio will be and the higher potential peak losses via drainage will be. If critical source areas producing runoff are dominant, most losses will be via runoff or erosion.

Plant protection products

- Degradation kinetics: DT_{50}

This factor can be more important than adsorption strength when transport is mainly via preferential flow due to the kinetic aspects of adsorption. DT_{50} is the key factor between application and the first significant rain event, as it controls how much PPP is available for transport into the soil. Degradation rate measured in the laboratory can however be quite different from actual degradation rates due to different environmental conditions and / or bacterial communities. As DT_{50} can range from a few days to more than 100 days, it is important to think about its impact as an order of magnitude. In the best case, the first rain event, which may mobilize PPPs after application, will happen in the order of 10 days later. This means that a well-chosen application date can have a big impact on losses of PPPs with a DT_{50} of 1 day, but appears negligible for PPPs with a DT_{50} of 100 days.

- Adsorption strength: K_{oc} (adsorption constant related to OC content)

The effect of adsorption strength is quite complex. One would initially think that the stronger the sorbing capacity, the better. Some studies, however, have shown that strongly sorbing pesticides can be rapidly transported to the drains via adsorption to colloidal soil particles (i.e. Larsson and Jarvis, 2000).

For total losses, the relationship tends to be more straightforward. Kladivko et al. (2001) showed that *"The total amounts of pesticide lost in subsurface drain flow during the 1985–1986 crop year were < 1% of the applied carbofuran and <0.1% of the applied atrazine, cyanazine, and alachlor. The rankorder of total mass losses corresponded with the rankorder of adsorption coefficients in a similar manner as the flow concentrations."*

- Volatility:

This parameter influences, along with spraying technique, losses via drift. Volatility controls, in combination with plant uptake and evapotranspiration, how much PPP will remain available for transport via runoff or through the soil. It ranges widely between products and formulations.

Crops

This interpretation of the individual impact of different crops is based on the qualitative analysis of lysimeter data in Switzerland and some general cropping practices. In Table 7, when a "+++" rating is given, it means that the more area planted with a specific crop, the higher the potential for peak PPP losses via drainage will be. The typical intensity and frequency of PPP spraying is here taken into account in combination with the soil cover of each crop. Specific growth phases throughout the year are therefore also critical.

We did not assess specific crops such as orchards and vineyards because we assume that most of those lands are not drained.

- Temporary grassland

This culture is important in the Swiss crop rotation. It represents 32% of the utilized agricultural area (FSO, 2020) and therefore concerns drained areas. It is usually not sprayed with PPPs and represents therefore a very low risk of PPP losses.

- Winter rapeseed and winter cereals

Their high water consumption leads to low drain flow through the growth season. They present less risk for surface sealing with silty soils as they are already well developed in the spring.

- Sugar beet and maize

Despite the inherent differences in the cultivation as well as the physiology of those two crops (spraying behavior, technique needed and root structures), we assessed them in a similar risk range with regard to PPP losses via drainage. Both develop in late spring, leaving a high proportion of uncovered soil into early summer. This leads to a low crop interception and hence to an additional risk of surface sealing due to low soil cover. Consequently, drain flow in spring in combination with spring PPP treatments may occur. In addition, both crops a have a high water consumption in late summer preventing drain flow at the end of the season. Specifically, sugar beet requires a comparatively higher amount of fungicides than most of the other field crops.

- Vegetables and potatoes

They are generally intensely sprayed and require intense soil preparation. They also have a tendency to cover the soil less ground on the fields than cereals and rapeseed during parts of the cultivation. For those reasons, we ranked them to higher risk of losses. Vegetable growing areas, however, make up a small share of the total utilized agricultural area only. In addition, some vegetable growing regions such as “Seeland” have such a high SOC content that PPP losses are low due to high adsorption.

- Soil cover

The more soil surface area covered by crops, the less erosion and runoff will take place. This leads to more infiltration. The presence of cover crops will also promote earthworm activity and, consequently, macropore flow through earthworm burrows. This should lead to more losses of PPPs via drainage but we consider here that cover crops are not treated. If those crops are be treated, a high soil cover would enhance crop interception of PPPs. Additionally, more biological activity will lead to quicker PPP degradation of products that might remain from the previous crop. We must however keep in mind that the long-term effect of cover crops on PPP losses via all flow paths is, similarly to reduced tillage practices, difficult to assess.

Agricultural practice

- Tillage intensity (moldboard plowing, reduced, no-till)

No-till will lead to more preferential flow but potentially less surface runoff. As the least sorbing pesticides are easily mobilized by surface runoff, we can imagine that PPP losses with tillage would be worse for PPPs with low adsorption strength, whereas losses would be worse for medium adsorption PPPs in the case of no-till. On the other hand, Kördel et al. (2008) concluded that there was no significant difference between no-tillage and conventional tillage (moldboard plowing) with regard to PPP losses via drainage (peak concentration as well as total loss). They assess that the slightly higher number of higher losses in no-till studies is in the range of randomness. With reduced tillage, the depth and/or area tilled is reduced.

We listed this practice as less risky than no-till with regards to PPP losses, because by destroying soil structure, tillage can help break permanent macropores. On the other hand, it temporarily tends to increase hydraulic conductivity of the tilled layer. Shallow tillage could make in this regard a good compromise. Alletto et al. (2010) provide a comprehensive review of the impact of various types of tilling practices. Their study mainly shows how complicated this question is. We discuss this aspect in more details in the section about mitigation measures (Section 4.2).

- Time between PPP application and first intense rain event

The rating in Table 7 means that the longer the time between PPP application and the first intense rain, the lower the peak PPP losses. We listed this weather parameter as management parameters (highlighted in orange) because the farmer can have some influence on the application date based on the weather forecast. This is one of the most important parameter controlling both peak concentrations in surface waters and total leaching amounts of PPPs. Its impact on PPP losses is logically positively correlated to the impact of the degradation half-life duration DT_{50}.

The effect of the first rainfall will however be very different depending on its intensity (see next parameter). Lewan et al. (2009) discuss in detail the influence of the date of application and its impact on both soil moisture at application and time before the next heavy rainfall.

- Intensity of first rainfall after application

Rainfall intensity has a direct impact on the mobilization of pesticides. Low intensities will lead to matrix flow rather than preferential flow. This will give more time for adsorption and can provide rather immobile storage to pesticides. They can later be mobilized either through more soluble metabolites (Gassmann et al., 2013) or via desorption / exchange with macropores. Although it has the benefit of limiting pesticides losses via runoff or preferential flow to the drains, matrix pesticide storage can have the drawback of lower degradation rates due to less microbial activity and no more photo-degradation.

Preferential flow generally takes place with high rainfall intensity, when the local infiltration capacity is exceeded. The higher the intensity, the more likely preferential flow takes place. Of course, above a certain intensity, infiltration excess overland flow will also build up. Frey et al. (2011) suggest 2 mm precipitation per hour as the intensity above which preferential flow starts. A higher amount and/or intensity is required for surface runoff than for losses via preferential flow. If the groundwater table at the start of rainfall is below the tile drains, more infiltrating water (drain flow starts later than runoff; depending on soil type, not much water might be needed for a rise) is required to generate drain flow. If the groundwater table is initially above the drains, then less water will be needed.

On a drained surface, rainfall amounts required for surface runoff will likely be higher than for drainage as infiltration and drainage will first occur. If land that would benefit from drainage is not drained, then runoff formation will often be quicker than at other sites due to saturation excess overland flow.

- Soil wetness at application date

As discussed earlier, preferential flow can also take place in unsaturated soils. The impact of soil wetness depends on antecedent weather conditions and soil texture. Figure 21 tries to categorize those relationships. Shipitalo and Edwards (1996) found that the relative contribution of macropores to chemical transport and water movement was the greatest, when the soil was dry.
If the surface is crusted (i.e. with silty soils), infiltration into the matrix will be very low. Applied PPPs will remain available at the soil surface and will rather degrade by photo-degradation, if possible, than by microbial

degradation. An intense rain event will quickly create infiltration excess overland flow and often erosion. If macropores are present, especially in the form of shrinkage cracks (as evidenced in Reckenholz, Figure 24), some of the overland flow could end up as infiltration by macropore flow.

The difficulty in quantifying the importance of antecedent soil moisture is summarized by Hardie et al. (2011) who stress that the effects of initial soil moisture content are complex. Some soils can become water repellent when being dry whereas clayey soils present shrinkage cracks upon drying. However, in general, wetter soils tend to generate more macropore flow than dryer soils, due to reduced lateral losses into the soil matrix (Jarvis, 2007). Despite the possible attenuation of peak losses to drains due to temporary losses to a dry soil matrix, Nimmo (2012) concludes *“the hazard expected from unsaturated-zone spread of contamination could be underestimated in relatively dry conditions and overestimated in wetter conditions”.*

Another aspect that was omitted in Table 7 but can affect PPP losses

- PPP formulation

The formulation can have a strong influence on losses, if it delays the time when the PPP dissolves (Brown and van Beinum, 2009). If a first small rain event happens on an unprotected PPP, rainfall will have the beneficial effect of infiltrating the compound in the upper soil layers, where they will be less likely to be mobilized by preferential flow during the following storm. On the other hand, PPP degradation will be slower in the soil than at the surface. Formulations, such as starch-encapsulated compounds, will slow down degradation and may lead to delayed losses or higher seasonal losses. On the other hand, it may also protect the chemical from heavy rains and thus lead to attenuated peak losses (for further information on crop interception see FOCUS (2014) and EFSA (2017). Wettstein et al. (2016) found increased leaching from seed dressings compared to spray applications.

2.8.2 Conceptual flow diagrams

Figure 21 schematically describes the main relationships between processes governing hydrology and fate of PPPs. The impact of each parameter is shown as +/- whether it has a positive or negative correlation. Hydrological processes are highlighted in blue, soil processes in green, PPP processes in orange and the final potential consequences in terms of PPP losses in red. For a simplified version of the diagram, with fewer outcomes with regards to PPP losses, please refer to Kobierska et al. (2020).

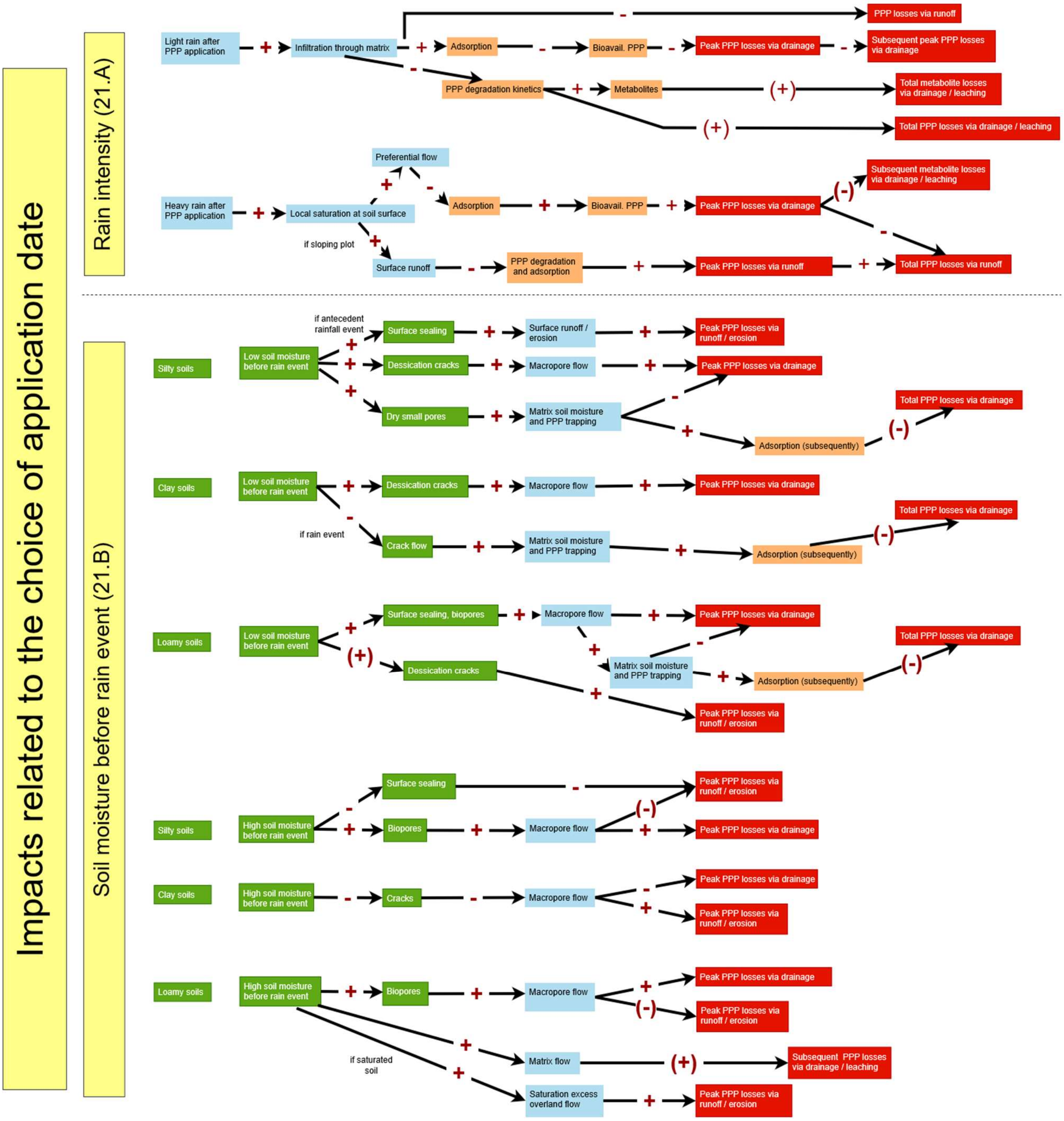

Figure 21: Conceptual model of PPP losses via drainage.

The focus is on the impact of the choice of the PPP application date (in yellow). Parameters and processes in green, blue and orange relate to soil, hydrology and PPPs, respectively. The consequences in terms of PPP losses are shown in red. "+" means an increase of the destination box: for example, more infiltration through the soil matrix leads to more adsorption of PPPs. "-" means a decrease and +/- conflicting effects. (+) means that the increase is weak.

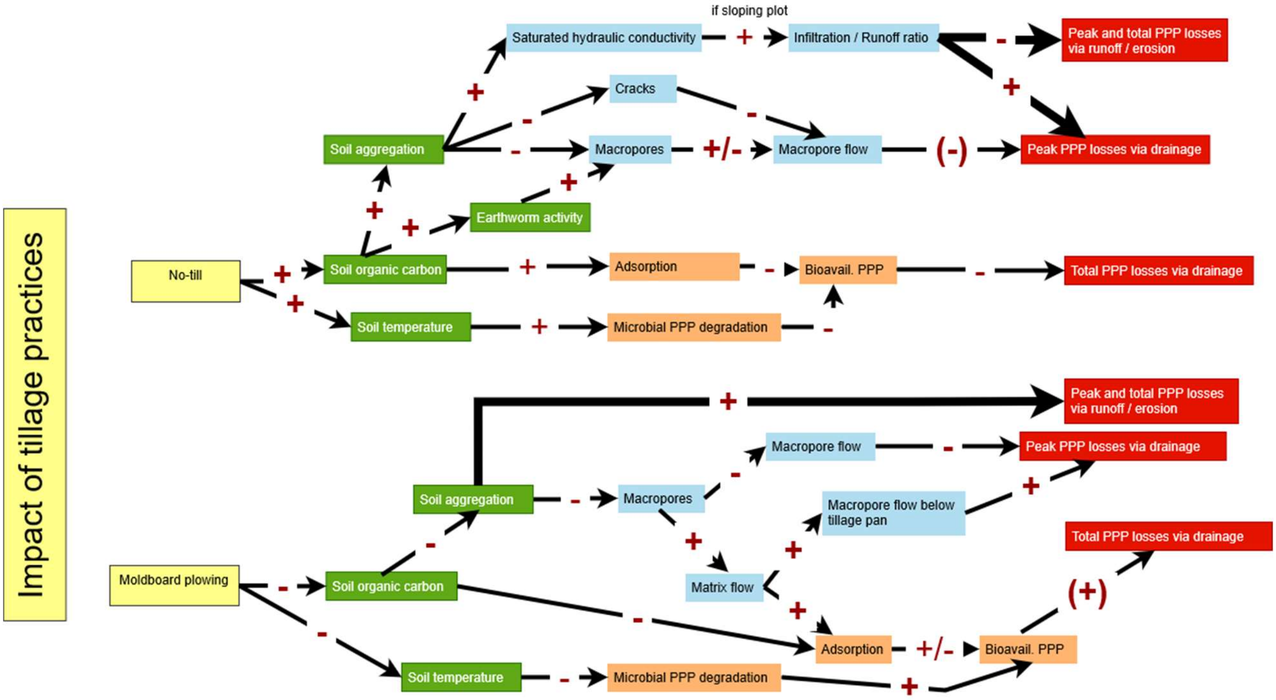

Figure 22: Flow diagram related to the impact of tillage practices on PPP losses. Refer to Figure 21 for the color code. The bold arrow shows a strong increasing impact.

Impact of rainfall intensity based on the conceptual model (Fig. 21.A)

Light rain after PPP application has some conflicting effects such as decreasing the potential of photo-degradation. It is however much better than heavy rain from the perspective of PPP losses via drainage, which leads to less adsorption, photo-degradation and microbial degradation, more preferential flow and more runoff.

The intensity and sequence of rain events following PPP application have a clear influence on leaching and drainage losses. In many studies involving artificial irrigation, the rain intensities used are however so extreme that they correspond to very rare events (more than 20-year return periods). The probability to be taken into account is not only the return of a specific storm duration and intensity, but also how likely it is to happen in a specific season, or worse, in the context of a favorable 5-day weather forecast. The impact of weather in the literature is therefore likely exaggerated in comparison to the best practice most farmers are aiming for.

Shipitalo et al. (2000) however point out that the probability of a rainfall with a long return period occurring shortly after pesticide application, is much lower than the estimated return period for such an event because return periods are usually based on the annual probability of occurrence.

Preferential flow generally takes place during high rainfall intensities but not necessarily on fully saturated soil, because only local saturation at the soil surface is required to initiate macropore flow. Especially if the soil surface is crusted (i.e. on silt-rich soils), preferential flow can happen while the matrix is still far from saturated. Frey and Rudolph (2011) suggest 2 mm precipitation per hour as the intensity above which preferential flow starts.

The rainfall pattern following PPP application is a very important parameter. The time between application and the first heavy rainfall controls, in combination with the degradation rate of the PPP (DT_{50}), how much PPP will remain available for mobilization. A second important aspect in fields that are susceptible to preferential flow is whether the first event is intense or not. If the first event is weak, water and dissolved PPPs will infiltrate into the matrix. If, in relation to soil dryness, total precipitation is small, dissolved PPPs will remain in the topsoil, where they will degrade quicker than on a dry soil surface. Further, for sites prone to preferential flow, a small first rain event will diminish the amount of PPP available for later mobilization via preferential flow. For those reasons, PPP application before a short duration and low-intensity precipitation event is generally favorable with regards to PPP losses in the soil. Therefore, peak and total PPP losses via drainage should be diminished.

Important processes are therefore those controlling the development of preferential flow. Biopores are directly related to the activity of earthworms. Macropores resulting from decaying roots will be more important in case of no-till or with soil of high SOC. In clayey soils, biopores will be less important but the soils will be prone to cracking upon drying. Upon rewetting, cracks disappear whereas biopores remain, which make clayey soils more sensitive to weather patterns than loamy soils. Silty soils may develop a crust upon drying, which can lead to surface erosion and/or to concentrated preferential flow if enough contiguous macropores have developed.

Impact of soil moisture before a rain event (Fig. 21 B)

In Figure 21, pre-event soil moisture is assigned contradictory effects on preferential flow because those effects depend on soil texture and past weather conditions. If soil moisture is low before the heavy rain event, clayey soils will present shrinkage cracks, leading to high rates of preferential flow. If the connectivity between the cracks and the drainage system is low, infiltrated water may however be retained into the dry soil matrix instead of contributing to drain flow. This would limit PPP losses via drainage. In silty soils the risk will be that surface sealing has developed facilitating runoff and erosion, both contributing to high peak PPP losses, mostly not through drainage.

On the other hand, if soil moisture is high before the rain event, shrinkage cracks in clay will have closed which should mean less preferential flow. Loamy soils that are rich in biopores will however retain those under wet conditions. This should lead to both high peak losses and high total losses as interaction between macropores and the matrix will be much lower than for a dry soil.

The connectivity of the macropores to the depth of the tile drains or even deeper is also highly relevant for discharge in tile drains (Zehe and Flühler, 2001). Ten centimeter deep cracks will cause fast flow of water from the soil surface to a depth of 10cm, but in absence of any other preferential flow pathways, matrix flow will be responsible for drainage discharge.

Impact of tillage practices (Fig. 22)

We see for example that no-till has conflicting effects on the fate of PPPs. More SOC leads to more microbial degradation but lower surface temperature can have the opposite effect. We further discuss the influence of tillage on PPP losses to waterways in Section 4.2 (mitigation measures).

3 Field experiments and characteristics of drained sites in Switzerland

In Switzerland, there are only a few studies dealing with PPP losses in drains or similar transport processes. There is a drained trial field at Zürich-Reckenholz, where various experiments have been made to investigate concentrations and total losses of PPP or other substances via drains. Further, Zürich-Reckenholz has various lysimeter experiments, which provide insights into PPP transport via measurements of concentrations and loads. Furthermore, there are various "resource" projects (Leimental canton Basel-Landschaft, AquaSan canton Thurgau, canton Bern) that are investigating, among others, PPP losses via drainage. However, no measurement results are yet available from those projects.

3.1 Drainage experiments at Zürich-Reckenholz

Several experiments have taken place at an instrumented drained field near Zürich-Reckenholz, north of Zürich (47°25'74" N, 8°30'85" E). However, most of the experiments did not involve PPPs. Bucheli et al. (2008), Hartmann et al. (2008) and Schenzel et al. (2012) focused on mycotoxins, Hoerger et al. (2011) on the estrogenic compounds isoflavones and coumestrol (COU). Wettstein et al. (2016) was the only study that focussed on PPPs (see Section 2.6 on the model EXPOSIT).

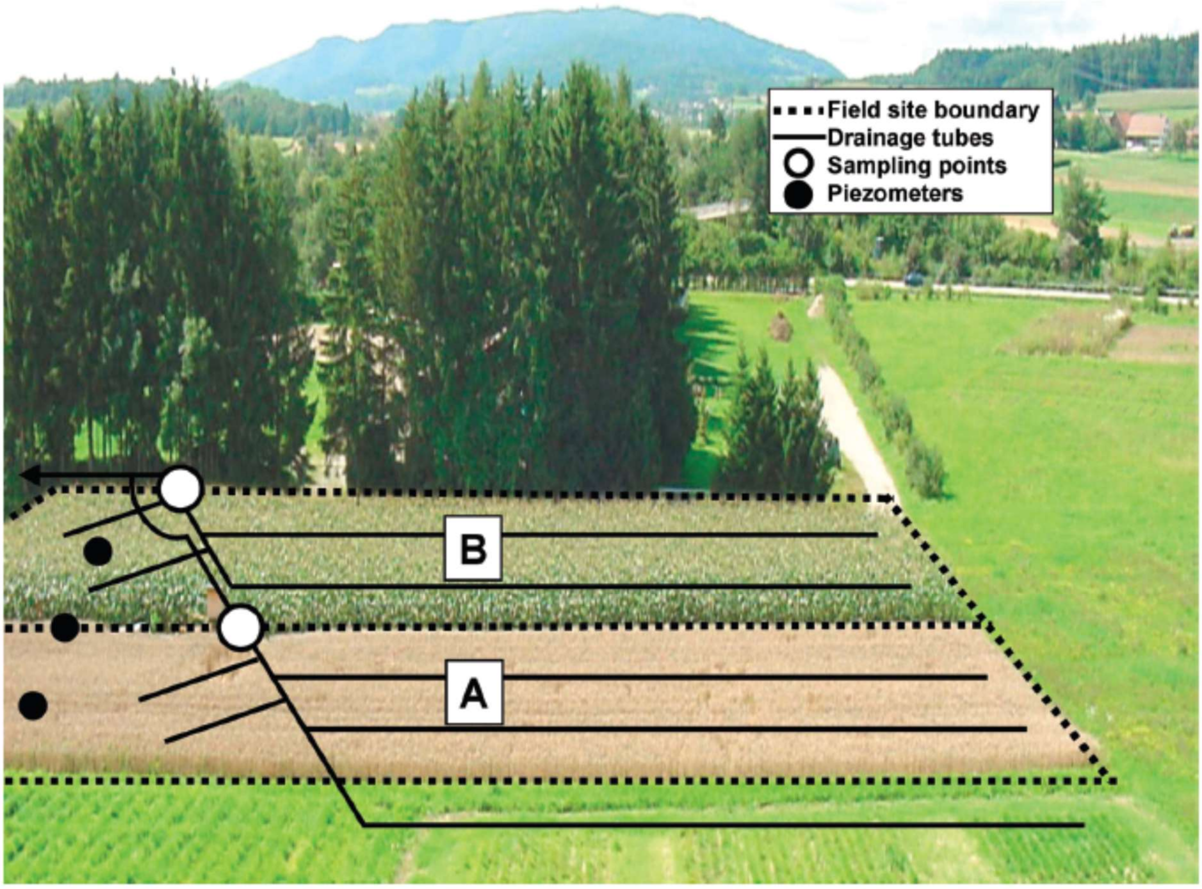

Figure 23: Field site at the research station in Zurich-Reckenholz, divided in two plots (A and B). Dashed lines: field site boundaries; solid lines: drainage tubes; open circles: sampling ducts; and solid circles: piezometers. Figure from Hartmann et al. (2008).

Schenzel et al. (2012) describe the experimental setup as follows: *"The two adjacent but separately drained fields of 0.2ha exhibit a gentle slope of 1–2°. The top soil of both of these test sites was classified according to the World reference base for soil resources and shows characteristics of a medium to heavy textured gleyic cambisol with 31% clay, 30% sand, 39% silt, and an organic carbon fraction of 2%."*

"Both test fields were drained by two long and two short drainage tubes, which individually connect to a main drainage tube with a diameter of 15cm. The drainage tubes are located in a depth of 80–90cm. The ground-water table depth ranged from 100–125cm and thus was permanently below the drainage system."

"Precipitation data were gathered by the meteorological station (Reckenholz 443 m above sea level, 47°25 ` 40" N, 8°31 `04" E"

Discharge drainage water was sampled flow proportionally. The soil at Reckenholz is a clay loam according to the USDA soil texture triangle (USDA, 2020), and a loam or clay loam according to the Swiss soil texture triangle (BGS, 2010). The drainages were installed 80 to 90 cm deep because a clay layer 1.2m deep acted as an impending layer. According to the TOPPS decision tree presented in Section 2.7, the risk should be low to medium based on the clay content, although cracks smaller than 1cm can form as illustrated Figure 24.

Figure 24: Picture of a wheat field at Reckenholz, August 27th 2019. The loamy soil shows spaced cracks in the order of a few millimeters wide.

In Hartmann et al. (2008) the following conclusions were drawn with regard to drainage flow of the mycotoxin zearalenone (ZON): *"In general, two stages could be distinguished in the ZON elution dynamics: (i) at certain times, especially during wheat and maize cultivation periods, ZON concentrations in the drainage water were in correlation with the drainage water discharge (first flush effect). (…). Together with the considerable sorption behavior described previously, this leads to the conclusion that ZON emission was mainly driven by preferential flow via macropores. (ii) In periods with no or little precipitation, a permanent baseflow of some* *milliliter per second drainage water was measured. During this time, ZON levels were almost always below the detection limit of 0.5ng/L."*

The authors conclude the total losses of zearalenone via drainage as follows: *"On the basis of ZON amounts in plant debris after harvest, assuming a negligible ZON production thereafter, and cumulative ZON loads emitted via drainage water in the following cultivation period, ZON fractions eluting via drainage water over individual cultivation periods can be calculated. These were 0.001% for the oil radish and maize cultivation period (August 18, 2005 to November 8 2006), 0.070% for the second wheat cultivation period (November 8, 2006 to July 23, 2007), and 0.040% for the investigated period after wheat harvest in 2007 (July 23 to August 15, 2007). These fractions were considerably lower than the 1.2% reported for deoxynivalenol (27), another Fusarium mycotoxin that we monitored simultaneously from July 9 to August 12, 2007."*

Bucheli et al. (2008) showed that drain flow was activated by four significant rain events in the summer 2007 (mid-June to end of July). This confirms that heavy or prolonged rainfall, which are not rare in Switzerland during summer (MeteoSwiss, 2020), can result in drain flow. The delay between rain event and drain activation was not studied. They concluded by comparing the behavior of mycotoxins to PPPs: *"To further evaluate the significance of the presence of mycotoxins in the agro-environment, their amounts and concentrations detected in drainage and river water can be compared to those of pesticides. First, the 50 and 15g/ha of deoxynivalenol and zearalenone present on a severely contaminated wheat field are, although at the lower end, comparable to the application rates of pesticides used: in Switzerland, atrazine is applied up to 1kg/ha, whereas certain more modern pesticides are used at amounts as low as 50g/ha. Second, the fraction subject to runoff of 1.2 and 0.02% for deoxynivalenol and zearalenone are well within the range of relative losses of the three commonly applied herbicides atrazine, dimethenamid, and metolachlor in smallscale catchments draining into river Aa (0.0002-1.0%) (Leu et al., 2004b). Third, concentrations of deoxynivalenol of up to 20ng/L as found in rivers of the Canton of Zurich are comparable to those of pesticides. For instance, 50% of all atrazine values (n = 653) ranged from not detected to 50ng/L. A total of 11 of 54 analyzed pesticides were never detected, and 6 others were only occasionally detected with maximum concentrations of <50ng/L."*

Hoerger et al. (2011) focused on isoflavones and coumestrol (COU*). Isoflavones and* COU are estrogenic compounds that are naturally produced by plants (e.g. red clover, soybeans). *"Total losses were low but first flush effects were visible for individual rain events. Mean isoflavone concentrations in drainage waters were roughly a factor of 20 higher than those observed in Swiss rivers, presumably because less dilution occurred."*

Schenzel et al. (2012) investigated over nearly two years the occurrence of various mycotoxins in a field cropped with winter wheat, which was artificially inoculated with *Fusarium* spp., as well as their emission via drainage water. Only the more hydrophilic mycotoxins or those prevailing at high concentrations were detected in drainage water. Total losses of mycotoxins recorded in drainage water were 0.002 to 0.12% of the total amount produced in wheat plants. Except for the experiment with fusarium in wheat by Schenzel et al. (2012), many of those experiments were conducted with the field grown as grassland rather than crops.

The study of Wettstein et al. (2016) was analyzed in detail in Section 2.6 about the EXPOSIT registration model. They found that every significant rain event in summer leads to drainage losses. Event-driven, high first concentration PPP-peaks suggested preferential flow. Mass recovery rates were however decreasing with increasing adsorption strength (0.003% to 1.2%). In addition, seed dressings led to higher losses than spray application. Wettstein et al. (2016) estimated the drainage efficiency at 61% with sugar beet (assuming a drainage relevant area of 2,600m^2, which was difficult to assess precisely), whereas Hoerger et al. (2011) measured 28% with a grassland – red clover mixture and Hartmann et al. (2008) 44% with a corn – wheat crop rotation. According to Hartmann et al. (2008), the average drainage efficiency in Swiss agricultural areas is 55%.

They come to the following conclusions regarding PPP losses via drainage at the Reckenholz site: *"This study convincingly showed that subsurface tile drains may contribute to the contamination of surface waters with neonicotinoids from seed dressings, especially for a field site that was prone to preferential flow and transport. The concentration patterns of the target substances revealed strong indications for this flow phenomenon, regardless of a spring or summer application.*

The time-lag to reach peak concentration was common for most PPPs irrespective of their physicochemical properties, whereas those properties still determined the total amount of drainage losses. The authors stress that although large parts of the filter and buffer capacity of the soil were bypassed owing to preferential flow, the soil matrix still contributed to a significant part of the total PPP losses. This highlights exchanges between macropores and the matrix. PPP ranking based on the GUS index value (see Section 2.7), rightly predicted a higher mass recovery in the tile drains for the neonicotinoids (point source) compared to S-metolachlor (diffuse source) during the experiment.

They finally suggest that point source applications such as with seed dressings may have a higher leaching potential compared to diffuse (spray) applications: *"On the one hand, seed dressings are less affected by losses due to wind drift or photodegradation, in contrast to conventionally applied pesticides; on the other hand, less favorable conditions prevail for degradation in the pill shortly after the application, and an enhanced mobility results as a consequence of higher local concentrations and nonlinear sorption behavior."*

There is ongoing work at the Reckenholz drainage facility within the PhD thesis of Daniela Rechsteiner with slurry derived steroidal hormones/natural estrogens (not published yet). Her data confirms that drain flow responds quickly to significant rain events (irrigation of 20mm in 2 hours), likely via preferential flow. The data is however inconclusive with regard to lag-times between precipitation and drain flow. It also appears very difficult to understand patterns affecting peak flow and peak concentrations in the drains. The infrastructure at Zürich-Reckenholz could help better understanding hydrological processes governing drain flow and related PPP losses. A specific experimental design involving soil moisture measurements is however required.

There is ongoing work at the Reckenholz drainage facility with the PhD work of Daniela Rechsteiner with hormones in manure (not published yet). Her data confirms that drain flow responds quickly to significant rain events (irrigation of 20mm in 2 hours), likely via preferential flow. Preliminary results also suggest comparable total losses to previous studies conducted at this site. The data is however inconclusive with regard to lag-times between precipitation and drain flow. It also appears very difficult to understand patterns affecting peak flow and peak concentrations in the drains.

For the 2020 growing season, the new project AQUATERRA will monitor, at the drained field of Zürich-Reckenholz, PPP losses via drainage of conventional potato culture (managed by T. Bucheli, S. Mangold and FOEN). A similar methodology to Wettstein et al. (2016) will be followed to measure PPP losses. In addition, FTR probes (frequency domain reflectometry) have been installed on the grassland bordering the field to monitor soil moisture variations. The project may run for two or three seasons if the results and methodology appear promising. We think this is important as the infrastructure at Zürich-Reckenholz is unique in Switzerland and could help better understand hydrological processes that govern drain flow and related PPP losses.

3.2 Lysimeter experiments at Zürich-Reckenholz

Agroscope maintains two lysimeter facilities at the Reckenholz site. As the lysimeters are weighable and equipped with probes for soil water conditions at different depths, water balances, transport processes and leaching loads of nutrients and pollutants can be measured.

The results can also be used as proxy for PPP transport in drained areas, as the depth of the lysimeters is similar to the depth of the local drains.

Lysimeter facility with 12 lysimeters

The facility consists of 12 weighing backfilled gravitation lysimeters (3.1m^2 surface area, 2.5m depth, 14,000kg soil in each). Six of the lysimeters (L1-L6) were filled with a well-drained Cambisol (sandy loam) developed from a stony alluvium (gravel soil), and the other six (L7-L12) were filled with a poorly drained Cambisol (loam) developed from moraine deposits (moraine soil). The two soil types are widely used for farming in Swiss lowlands and mainly differ in the texture of the B-horizon and the draining properties of the parent material.

The main goal of the study of Torrentó et al. (2018) was, to evaluate the suitability of different tracers as proxy for PPP transport in arable soils by comparing their behavior with a model PPP (atrazine) in outdoor lysimeters during a 2.5yr period. Conditions for preferential flow were promoted by applying heavy simulated rainfall shortly after pesticide application. In some of the experiments, preferential flow was also artificially simulated by injecting the solutes below the root zone. At the end of the monitoring period (900 d after application), an average of 0.7% of the surface-applied atrazine mass was recovered in the drainage water (0.2% for the gravel and 1.2% for the moraine soil). Higher recoveries were obtained with depth injection: 2.3% for the gravel and 2.4% for the moraine soil. The rapid preferential atrazine breakthrough was more significant for the moraine than the gravel soil and, as expected, more evident after depth injection. Preferential flow through macropores, which are likely to occur in the moraine but not in the gravel soil, seems to be the most likely explanation of the results.

For the study of Melsbach et al. (2020) with application of Desphenylchloridazon (DPC), the main metabolite of the herbicide chloridazon (CLZ), six of the lysimeters were used. In contrast to the study of Torrentó et al. (2018), no rapid breakthrough peak was observed shortly after application for DPC. Additionally, DPC breakthrough curves give evidence that DPC leaching was mainly driven by porous matrix flow, although intense irrigation events resulted in a greater contribution of preferential flow. This was observed mainly in moraine soil. The drainage volume represented 25–39% and 18–27% of the total irrigation, respectively. Soil humidity data revealed that large irrigation events resulted in a greater contribution of preferential flow on drainage, and that this effect was more significant for the moraine than for the gravel soil. Approximately 0.5% and 0.13% of the applied CLZ was leached as DPC after 950 days in gravel and moraine soil, respectively.

Lysimeter facility with 72 lysimeters

This lysimeter facility was built in 2009 and contains 72 lysimeters with a surface area of 1m^2 and a depth of 1.5m. The free draining gravitation lysimeters contain natural undisturbed soil up to a depth of 1.35m. The deepest 0.15m are filled with sand and gravel to enable free drainage. All lysimeters are used for agronomic experiments. The main focus is on water flow and nitrate leaching under different cropping systems, soil tillage practices and fertilization regimes. Over the last ten years, most crops of the traditional Swiss crop rotation have been grown. The three soil types are loamy soils and widely used for farming in Swiss lowlands (Prasuhn et al., 2016, Oberholzer et al., 2017).

The average precipitation in the years 2009–2019 was 977mm (Tab. 8), the corresponding amount of seepage water on the lysimeters was 365mm. On average, 37% of the precipitation percolated, with a range of 29–49% per year. The highest amounts of precipitation occurred during the summer months. Due to the high evapotranspiration, however, the seepage amounts are lowest in the summer months.

Table 8: Average monthly precipitation and leachate over 10 years (2009-2019) on all 72 lysimeters at the lysimeter facility of Zürich-Reckenholz, Switzerland.

	Precipitation (mm)	Leachate (mm)	%
Jan	79	69	88
Feb	46	52	112
Mär	51	38	75
Apr	59	22	36
Mai	116	30	26
Jun	113	19	17
Jul	121	11	9
Aug	92	6	7
Sep	72	8	12
Okt	62	12	19
Nov	76	29	38
Dez	90	68	76
Total	977	365	37

The relatively high yearly precipitation in the measurement period from 2009–2019 with 796–1,165mm are quite well distributed throughout the year. Although drainage is rare in summer, it can happen during wet summers, depending on which crop has been planted. Figure 25 shows an example of the monthly distribution of drainage flow from a selected lysimeter at the facility.

The analysis of the lysimeter data further shows that there are also quite large differences in drainage flow depending on the crop. Maize and sugar beet are typically the crops that leads to the highest spring drainage losses, due to late plant development and their long growing season. This is the contrary for cereals, and especially winter cereals, which develop (and are harvested) earlier. Autumn drainage is the most likely with those crops. Oilseed rape develops very early and leads to minimal losses throughout the season.

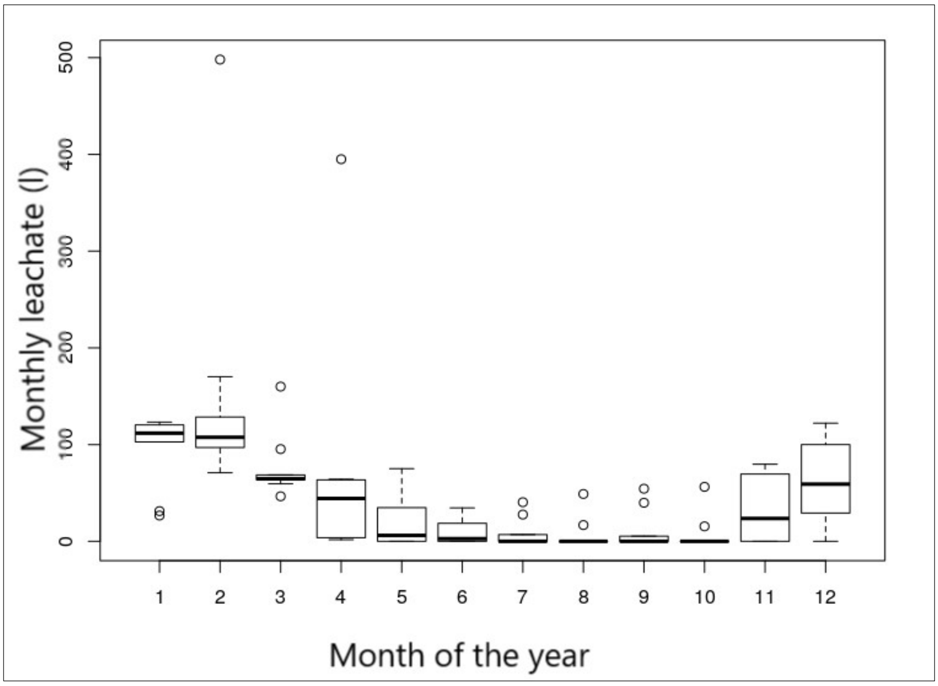

Figure 25: Boxplot of the distribution of drainage flow throughout the year. Data shows lysimeter number 3 at Reckenholz for the measurement period 2009 to 2019.

3.3 Characteristics of drained sites in Switzerland

3.3.1 Soil properties

Most agricultural soils in Switzerland are sandy to clayey loams, mainly luvisols and cambisols. Clay soils (> 35% clay content), which tend to swell and shrink and thus to increase macropore flow, hardly occur. Such clay-rich soils exist mainly in the Jura. However, these soils are mostly used as permanent grassland, are often relatively shallow and are generally not drained. They are therefore of little relevance to the present research question. On the other hand, there are no sandy soils, which typically show more homogeneous flow patterns and matrix flow. Loess soils occur only locally in northwestern Switzerland (see Konz and Lang, 2018). Correspondingly, the agriculturally used and potentially drained soils in Switzerland are rather similar in terms of water and solute transfer processes (macropore flow, matrix flow, soil depth). They mostly fall into the medium risk class of the decision tree presented when considering the current European Union assessment model to evaluate the risk of drainage losses in agricultural fields from TOPPS (see Section 2.7).

Today only 13% of the utilized agricultural area in Switzerland has good quality digital soil maps (Rehbein et al., 2019). Since only a few cantons also have data on drained areas in digital form, a detailed analysis of soil properties and drained land was only possible for the canton of Zurich (Koch and Prasuhn, 2020). Results show that there is only limited correlation between drained areas and soil properties or soil types. Wet soils with periodically high groundwater table (cambisol gleys such as “Buntgleye”, “Fahlgleye” or “halb-Moor”) are the most frequently drained at 50%. However, reasonably permeable deep soils (cambisols and luvisols) which occur most frequently in the canton of Zurich, are also partly drained. Other influencing factors, such as the topographic position (top or bottom of slopes) can therefore justify drainage despite favorable soil properties.

A soil map for Switzerland as a whole is available at the 1:200,000 scale (BEK200; FOAG, 2012). The comparison between soil properties and drained areas was carried out for around 93,000ha (Koch and Prasuhn, 2020). Most drained areas can be characterized by specific properties in the BEK200. The drained areas usually show signs of waterlogging, have good or very good water storage capacity, low hydraulic conductivity, are deep and low in skeletal structure. However, not all areas that have these characteristics are well drained. Likewise, there are numerous drained areas which, according to BEK200, have other properties that do not suggest a need for drainage. Soil properties of the BEK200 alone are no clear indication of whether a surface is drained or not. Other properties, such as topography must be taken into account. Furthermore, spatial inaccuracies due to the poor resolution of the BEK200 must be kept in mind in this comparison.

The analysis of the map of the potentially drained areas of Switzerland created by machine learning also showed that soil properties did not play the most important role in the determination of potentially drained land (Koch and Prasuhn, 2020). Topographic wetness index or slope had the biggest influence here.
In Szerencsits et al. (2018), the potential for wet agricultural land in Switzerland was determined by means of a GIS analysis. In a first step, soil maps, geology, inventoried wetlands, drained areas and historic wetlands were blended with the hectare raster of arable land from Swiss area statistics and evaluated in 4 classes (Table 9). From this, 18% of the arable land was attributed a high potential for wetland based on these criteria. Wetlands were classified as possible for 11% of the land and as unlikely for 27%. The remaining 44% of arable land could not be classified, as there were no detailed soil maps. In a second step, relief parameters (slope in percent, maximum gradient in a radius of 25m and height difference to the lowest point in the field block) and precipitation parameters (average annual precipitation) were intersected with the hectare grid of arable land from the Swiss areal statistics and evaluated in 5 classes (Table 9). The 5th category (high potential) comprised 13% of arable land which have a high likelihood of being drained. This encompasses the plains and the bottoms of geomorphologic depressions. For 40% of the arable land, a low relief-related potential was determined. These are mainly slopes and hills that drain readily by gravity.

Table 9: Potential for wet agricultural land in Switzerland based on data from the “Arealstatistik” (FSO, 2017), depending on different classes of soil / geological data availability as well as topographic and precipitation indices. Adapted from Szerencsits et al., 2018.

potential			arable land	
soil/geology		**topography/ precipitation**	**ha**	**% ot total arable land**
existing	**18.0**	**5 high**	21‘061	5.4
		4	18‘705	4.8
		3	10‘751	2.7
		2	7‘189	1.8
		1 low	12‘826	3.3
likely	**11.0**	**5 high**	7‘078	1.8
		4	8‘383	2.1
		3	7‘881	2.0
		2	7‘283	1.9
		1 low	12‘530	3.2
unlikely	**27.0**	**5 high**	12‘788	3.2
		4	18‘981	4.8
		3	19‘003	4.8
		2	19‘066	4.8
		1 low	36‘985	9.4
uncertain	**44.0**	**5 high**	9‘503	2.4
		4	16‘519	4.2
		3	24‘010	6.1
		2	29‘214	7.4
		1 low	93‘884	23.9
		total	**393‘640**	**100**

3.3.2 Topographical properties

The intersection of the map of drained areas in Switzerland with the digital terrain model DHM25 shows that with about 73.4%, the largest part of the drained area lies at levels <10.5% slope (Koch and Prasuhn, 2020). A 10.5% slope however is already quite steep, steeper than the 3% limit suggested by the DPR2 tool (Guiet and Falchier, 2018) to partition between runoff and infiltration. In addition, for the 10 cantons that have data on drained areas in digital form, 28.3% of the drained area lies in land than is less than 2% steep (Koch and Prasuhn, 2020).

It should be kept in mind that local slopes leading to the flatter drained areas can produce runoff, which could then mainly infiltrate in drained areas if those are located in a bowl. Groundwater can also infiltrate into drains via subsurface lateral flow. In this case, precipitation would have infiltrated into the shallow subsurface at locations far upslope from the drain and would have flowed towards the drain along a low permeability layer and/or via lateral macropores.

3.3.3 Precipitation

According to Szerencsits et al. (2018), average precipitation levels on arable land (based on areal statistics FSO, 2017) range from around 600mm in Valais to around 2,000mm in Ticino. The mean value is 1,173mm with a standard deviation of 151mm. The rather high mean yearly rainfall (i.e. in comparison to Germany) tend to lead to a higher risk of PPP losses via drainage.

3.3.4 Geology and Hydrogeology

The overlapping of the map of the drained areas of Switzerland with the geological map of Switzerland shows that the largest part of the drained area lies above moraines. However, many drained areas are also located on (former) wetlands, swamps, bogs, peat moors and alluvial geologies (alluvial, fluvial, fluvio-glacial) (Koch and Prasuhn, 2020).

The hydrogeology report for Switzerland (Jäckli and Kempf, 1972) discusses local hydrogeological situations. An important aspect to consider when assessing the potential impact of drainages on water quality is the typical hydrological behavior of the drainage as shown in Figure 6. Has the drainage been installed to drain a perched water table because of a near surface gleyed soil horizon? A gleyed horizon at 1–2m depth is reasonably frequent in Switzerland. Or has the drainage been installed because of a seasonally high groundwater table? Drainage in the “Seeland” region has been installed for this latter reason.

3.3.5 Drainage type and depth

Béguin and Smola (2010) present the results of a quantitative and qualitative survey on the state of drainage in Switzerland. The authors found out that with regard to the agricultural land best suited to arable crops (“Fruchtfolgeflächen”, FFF) and according to a conservative estimation of the FOAG, the results of the survey show that about 70% of the drained areas are FFF and 30% of the FFF are drained. The survey also revealed the following facts: 80% of the drained areas are in the valley zone, 12% in the hilly and mountainous zone, 8% in mountain zones II to IV and in the summer grazing area. The evaluation by the cantons reveals that 35.5% of the drainage systems, corresponding to about 68,400ha, are currently in poor or unknown condition. Almost half of the drainage systems are still in good condition.

Drainages can consist of subsurface pipes (tile drainage) or open ditches. Both are used in Switzerland (Seitz, 2013; Gramlich et al., 2018) and in Europe, but most of the literature deals with drainage losses through tile drainage (Brown and van Beinum, 2009). Subsurface drains are the most represented in Switzerland. Open ditches installed for drainage are mainly to be found in drained swamps such as in the drained moors of the “Seeland” region. They are less affected by vertical preferential flow and will receive both surface runoff and subsurface lateral flow. The flow paths leading to them will likely be longer and more prone to adsorption than those of tile drains. In clayey soils, mole drainage is sometimes used instead of tile drainage. This technique is however negligible in Switzerland due to the rarity of heavy clay soils.

The project dealing with the computation of a drainage map for Switzerland (Koch and Prasuhn, 2020) showed that there is a relatively high uncertainty for the exact location of drainages. The depth to the pipes is therefore even more uncertain. It however appears that many drains are around 1 to 2 meters deep in Switzerland (Seitz, 2013). This would be an important parameter to evaluate more precisely as the losses depend very strongly on this variable, especially when preferential flow is dominant as described in Section 2.3.

4 Mitigation measures against PPP leaching to drainages

4.1 Overview of available mitigation measures

Several reports have compiled and evaluated various measures to reduce PPP entries. Ernst Basler and Partner (2015), Vision Landwirtschaft (2016), Spycher et al. (2015) and Prasuhn et al. (2018) are some of the key papers. In the international context, there are summarizing papers from TOPPS (TOPPS, 2018), MAgPie (Alix et al., 2017) and Reichenberger et al. (2007) as well as numerous papers that comment on individual measures (e.g. Tournebize et al., 2017). In the following, we summarize the literature and specifically analyze the measures in relation to drainage losses.

Based on a literature review, Ernst Basler and Partner (2015) identified, grouped and evaluated 85 individual measures for the reduction of inputs of pesticides into water. They covered the entire range of possible measures from PPP licensing to application and pathways to consultation, control and research. Many of the measures listed apply to all flow paths (drift, runoff, infiltration, drainage). For drainage, 11 measures are explicitly detailed. Most of these measures deal with registration and application of PPPs: application conditions for the use on drained areas, care in filling, accessing the field and cleaning equipment, checking of shortcuts to waterways, water tanks for flushing, storage and safe disposal of PPP, reduced use in greenhouses. Only two of the listed measures relate to agricultural methods and pathways:

- Seasonal restriction of the application of specific PPPs in certain meteorological conditions, for example prohibition of use in autumn.
- Retention of runoff and drainage water through wetlands and vegetated ditches on or near agricultural land.

The report of Vision Landwirtschaft (2016) does not show any specific measures in relation to drained land. It focuses on rather general measures: improving registration procedures, increasing data collection on the use of PPP, controlling and enforcing best management practices, strengthening ÖLN key concepts, and finally promoting production methods using less PPPs.

Spycher et al. (2015) differentiate between three approaches, namely reduction, substitution as well as optimization of cultivation and handling to reduce PPP inputs to waterways. The potential for substitution by other chemical PPPs is seen as limited and mostly beneficial to losses via drainage. Specific measures for drained areas are not discussed.

Prasuhn et al. (2018) have compiled a catalog of measures and assessed 27 measures with regard to knowledge status, applicability / practical suitability, acceptance by farmers, status of implementation in Switzerland and reduction potential of PPP losses via runoff and erosion. They restricted the analysis to runoff and erosion as the level of knowledge about drainage losses was unsatisfactory. The assessment of the mitigation measures was based on expert knowledge of experienced colleagues from various cantonal agencies. Overall, the state of research was considered relatively good for most of the measures, while shortcomings affect practicability, acceptance and, above all, implementation.

Reichenberger et al. (2007) cite Flury (1996) as follows:

- *“The mass lost by drainage or leaching seems, in general, to be smaller than that lost by runoff.*

- *Conservation tillage (incl. zero-tillage) had either no effect on pesticide leaching/drain flow or enhanced it compared with traditional tillage.*
- *The experimental evidence on the effect of pesticide formulation is not consistent. Controlled-release formulations may reduce the risk of pesticide transport by preferential flow, but might increase slow leaching later. Granular formulations yield a less uniform spatial distribution of pesticides at the soil surface than sprayable formulations, which also may affect the transport of active ingredient."*

Additionally, Reichenberger et al. (2007) discuss the overall effectiveness of combining mitigation measures. If they do not have efficiencies independent of each other and/or if they lead to increased or decreased pesticide losses via another pathway, then the overall loss reduction of a combination of mitigation measures is hard to predict. Shipitalo et al. (2000) note that most mitigation measures against PPP losses in surface runoff (mainly herbicides in this case), such as sub-residue placement, reduced application rates, banding and slow-release formulations, should also be effective in reducing losses to drainage through macropore flow.

MAgPie stands for „Mitigating the Risks of Plant Protection Products in the Environment" and is the result of two workshops on mitigation measures in Europe (Alix et al. 2017). Regarding drainage, the report mentions that: *"the processes dominating the transport of pesticides into the drainage system are however closely related to those determining the leaching into groundwater and as a consequence, the participants concluded that almost all the measures discussed for mitigating groundwater risk were also suitable for mitigating exposure via drainage water. These include restrictions on application rate or timing, soil type, band application, restriction of use in vulnerable areas". "However, there are some important differences that must be considered". "Subsurface drainage systems are most commonly established in areas with more heavy cracking clay soils where transport via macropore flow plays a major, and occasionally dominant, role."*

"One mitigation measure that can be applied to drainage but not leaching to groundwater is the use of retention structures including detention ponds, natural ponds, artificial wetlands and, potentially, storm water tanks. The purpose of such structures is to intercept drain flow either before or very soon after entry into surface water". "Design criteria published in France target a hydraulic retention time of 7 days and suggest that retention structures with an aerial extent of ca. 1% of the drained agricultural area and a depth of 0.8m will be sufficient to retain 7mm of drain flow (Tournebize et al. 2015)."

The TOPPS working group (TOPPS, 2018) presents a well-documented catalog of measures from several countries of the European Union on how to reduce water pollution with PPP from drainage and leaching. We have checked this catalog of measures for the applicability to Swiss geographical and agronomical conditions. Those measures and some other suggestions are compiled in Table 10. We analyzed their potential based on expert judgment in an analog manner to Prasuhn et al. (2018).

The TOPPS working group ranks mitigation measures in relation to the risk of losses. General measures and low risk measures are pretty much standard in Switzerland as part of the requirements for the 'Proof of Ecological Performance' (PEP). They link the risk assessment presented in Table 6 (see Section 2.7) to those measures. This could be a good tool for farmers to decide which measure is best adapted to their site. This illustration also helps combines losses by both runoff and drainage.

Table 10: mitigation measures against PPP losses via drainage (from TOPPS, 2018).

Measure categories	General measures	Low-risk measures	Medium-risk measures	High-risk measures
Adapt application timing	Do not spray if forecast		Avoid spraying during drainflow period	Consider alternative PPPs
Reduce substance load per field	Consider seed treatment options Consider spot treatment techniques	Use split applications Reduce rate to a minimum that maintains efficacy	Reduce rate via pesticide mixture	
PPP selection and rotation		Widen crop rotation in catchment	Rotate pesticide in specific crop	Restrict use of critical pesticides
Optimise crop rotation	Select rotation to optimise plant health	Consider crops with tap- and fibrous-root systems Alternate winter and spring crops		
Adapt tillage practice				Consider tillage to disconnect soil pores
Gorw cover crops	Select suitable cover crops			
Optimise drainage practice		Avoid over drainage		
Water-retention structures				Use retention structures to collect drainflow
Optimise irrigation practices	Calculate needed irrigation volume	Optimise irrigation scheduling based on soil moisture		

4.2 Assessment of mitigation measures

4.2.1 Description of each mitigation measure

Mitigation measures 1 to 9 in Table 11 are suggested and described in detail by the TOPPS working group (TOPPS, 2018). We therefore focus on assessing those measures for the Swiss conditions as well as suggesting some other potential avenues based on the literature. We suggest measures 10 to 13 as additional land use change options. The fourth column “state of knowledge” is an assessment of the literature knowledge on each specific measure. The second relates to its ease of implementation on the field. As in Prasuhn et al. (2018), the potential of the measures to reduce inputs of PPPs into surface waters is estimated in the 4th column based on its potential impact for the whole of Switzerland. The assessment was carried out in combination with column 3, which represents the measure potential per hectare area. Each measure can have a very large reduction potential in a given situation. If a measure has a high intrinsic potential (column 3) but is limited to very specific geographical and agronomical conditions, its significance for Switzerland will be low in column 4. Because the geographical extent of each measure is not presented in the table, the fourth column should not be expected as the sum of the first three.

Many of the remaining measures are not very well suited to the Swiss environment because they require either too much land or too much infrastructure and do not compete economically. Some would have high potential when applied on agricultural fields in Switzerland, such as shifting application dates. However, the realistic scope for farmers is small, especially during difficult growing seasons with much and frequent rain.

Table 11: List of mitigation measures (based on TOPPS, 2018), their specificities and applicability in Switzerland. The overall potential reduction is assessed for the whole country.

	Measure categories	**Specific measures**	State of knowledge	Applicability, practicability	Potential for reduction of PPP losses via drainage per Ha	Overall potential for reduction of PPP losses via drainage	Type of mesures and processes		
1	Adapt application timing	Avoid spraying during drainflow season and shortly before heavy rainfall is forecast Consider available treatment alternatives	++	-	++	+	eP	A	S
2	Reduce substance load per field	Reduce overall rate per area Use PPP mixtures (different active ingredients) Use split applications (strech PPP load) Use pest-monitoring techniques (manual, automatic sensors) and only treat infested areas (spot treatment) Use seed treatment	+	0	++	++	eP/pP	A	C
3	Optimise PPP selection and rotation in catchment	Widen crop rotation to reduce the load of a specific pesticide Rotate pesticide for a specific crop in the catchment Restrict pesticide application in vulnerable fields	0	0	+	++	eP	A	C
4	Optimise crop rotation	Select crop rotation to optimise plant health and - alternate winter and spring corps - consider plants with tap- and fibrous-root systems	+	0	+	+	eP	A	C
5	Adapt tillage practices	If drainflow is a problem: consider using at least shallow tillage to disconnect soil macropores in vulnerable fields	0	+	0	0	eP/pP	A	S
6	Grow cover crops	Select cover crops to fit the rotation of the main crops -pay attention to good cover crop - maintain and manage cover crop - ensure cover crop does not interfere with cash crop	+	+	+	0	eP/pP	A	S/C
7	Optimise drainage practice	Design drainage professionally (follow guidance) to avoid over-drainage	++	-	0	0	eP/exP	T	C
8	Use water-retention structures	Use retention structures (e.g. ponds, wetlands) to capture drainage water for retention, dilution and dissipiation of high-concentration drainflow pulses in autumn or summer	0	-	+	0	eP/exP	T	S
9	Optimise irrigation practices	Calculate the necessary irrigation volume (balance) Soil moisture monitoring to optimise irrigation scheduling	+	0	+	0	eP/pP	T	C
10	Soil amendment	Biochar	0	-	+	0	eP/pP	T	C
11	Land use change	Paludiculture	+	-	++	0	eP/pP	A/T	C
12	Land use change	Rice production	-	-	0	0	eP/pP	A/T	C
13	Land use change	Agroforestry	-	-	++	0	eP/pP	A/T	C

?	Uncertain	++	Very good
eP	whole plot	+	Good
pP	part of plot	0	Average
exP	neighbouring plots	-	Weak
A	agronomic		
T	technical		
C	Measure against causes		
S	Measure against symptoms		

1. Adapt application timing

Lewan et al. (2009) write that optimizing application timing is probably the only practical mitigation strategy against pesticide leaching. For autumn applications, they tested a simple criteria based on soil water deficit and compared this to restrictions based solely on application date. They found it more effective and acceptable to farmers (giving them more flexibility) to use a soil water deficit criteria, rather than restricting PPP application based solely on date. They suggest reducing pesticide losses by a factor of two to three could be achieved with better timing. However, soil moisture in autumn can be very high for prolonged periods, which may drastically reduce time windows for application. Acute ecological risk in surface waters following spring applications may also be reduced by a factor of 2–3 by avoiding application if 5-day weather forecasts predicting significant precipitation (e.g. >10mm).

It is however easier said than done, as the “timing” variable is not easy to control. In dry weather conditions, the application date can be chosen with some flexibility. When conditions are wet, there may be much less margin if the field is too wet to drive on. Wet conditions also lead to more fungal attacks and therefore increase the likelihood of spraying fungicide within a very small time-window. It is therefore a bit of a vicious circle.

With rapeseed, a 10-day window is generally available in spring for spraying herbicide. Winter wheat is usually not sprayed in autumn, as PPP application is not allowed in November. The window in spring is similar to rapeseed. With sugar beet, spraying herbicide is also not very flexible, as the plants need to be protected at the right time from fast-growing weeds. Spraying later in the season should be less of a problem to water contamination as ground cover becomes substantial.

In addition to adapting the timing of PPP application, Reichenberger et al. (2007) mention a reduced application rate (next measure) and substituting PPPs (measure number three) as the only feasible mitigation measures for drainage and leaching.

2. Reduce substance load per field

An important question to further investigate is whether there are priority zones where organic agriculture should be enforced / facilitated. With regard to drains, we consider that the current knowledge on drained areas and pollution processes is too uncertain to consider specific areas.

3. Optimise PPP selection and rotation in catchment

A diverse crop rotation at the catchment scale will ensure that different PPPs are used every year. TOPPS (2018) recommends alternating between winter and spring crops, tap- and fibrous-root crops as well as cereal and broad-leafed crops. Switzerland already enforces best practices with regard to crop rotation as part of the requirements for the ‘Proof of Ecological Performance’ (PEP). There is therefore probably less scope of improvement on this aspect in Switzerland than in other European countries.

4. Optimise crop rotation

Balderacchi et al. (2008) show the reduction in leaching when crop rotation is used. This point is also expressed by TOPPS (2018). In contrast to the preceding point, TOPPS focuses here on crop rotation for each individual field. There is not much margin of progress in Switzerland as crop rotation for each field is thoroughly practiced throughout the country. Mixture cropping can help reduce the amount of PPPs used as well as increase ground cover early and late in the growing season, which ultimately reduces the risk of drainage losses. This is a rather new field of research and its focus has rather been on productivity than on water quality so far.

5. Adapt tillage practices

This aspect was already partly discussed in Section 2.8, as part of the explanation of the conceptual model. Conservation tillage methods like reduced tillage and especially no-till, are according to the literature, undisputedly effective against PPP losses via soil erosion (i.e. in Switzerland: Prasuhn, 2012). Regarding losses via leaching or drainage, results are much more variable. The effect of no-till is hard to quantify but it may increase PPP losses to drainage as preferential flow through biopores. We illustrated in the flow diagram of Figure 22 the various potential impacts of changing tilling practices on the risk of PPP losses via drainage and runoff.

In Ulén et al. (2012), shallow tillage, a specific type of reduced tillage, is discussed. The soil is only tilled down to 5–15cm and the soil is not inverted as with full tillage. They assert that this leaves the soil surface covered with at least 15% of crop residues year-round. As the disruption of macropore continuity by tillage reduces the contribution of macropores to total flow, reduced tillage can be a good alternative to mitigate the potential of increased losses with no-till.

Shipitalo et al. (2000) state that conservation tillage can have a bigger impact on how water moves through the soil than on the total amount percolating to groundwater. “*Even under extreme conditions, it is unlikely that the amount of additional adsorbed solute transported to groundwater will exceed a few per cent of the application when conservation tillage is used instead of conventional tillage.*” The authors stress that soil macroporosity and the proportion of rainfall moving through preferential flow paths often increase with the adoption of conservation tillage and can contribute to a reduction in surface runoff. Indeed, Malone (2014) found higher atrazine concentrations in drain flow under no-till than conventional tillage conditions, whereas Potter (2015) states that surface runoff losses were reduced by one order of magnitude. Shipitalo et al. (2000) also note that no-till soils are usually denser and thus have a lower total porosity than frequently tilled soils. They however have well developed macro-porosity. The maintenance of a continuous residue cover also helps prevent crust formation, which helps reducing surface runoff and increasing the effectiveness of the remaining porosity.

The FOOTPRINT project (Dubus et al., 2009) noted that the effect of primary tillage on solute transport is small compared to the effect of secondary tillage for seedbed preparation. This show the important impact of secondary tillage on macropores and justifies its recommendation by TOPPS (2018) as a mitigation measure. Besson et al. (2011) look at the impact of more subtle differences in tilling than just no-till and intense tillage. They make the distinction between primary tillage (moldboard ploughing) and secondary tillage (harrowing) as Jarvis (2007) in his decision tree. They further point that persistent and intense rains can trigger preferential flow, even after fine seedbed preparation. This can happen along soil heterogeneities in well-aggregated soils, or at the compacted interface (plough pan) with the undisturbed subsoil (Besson et al., 2011).

The FOOTPRINT project (Dubus et al., 2009) concluded that most studies, but not all, have demonstrated an increased leaching of relatively mobile pesticides under no-till. They were however cautious about generalizing the effects of tillage on leaching by macropore flow. Intensive tillage tends to reduce aggregate stability and stimulate particle leaching in macropores. This may increase the leaching of strongly sorbed solutes prone to particle-facilitated transport such as glyphosate.

TOPPS (2018) have a good and clear summary on the potential effects of various tilling practices on PPP losses via drainage:
“*This means the influence of reduced tillage /no-till on runoff mitigation and drainage mitigation result in contradicting effects. If surface runoff occurs on a drained field, its prevention takes precedent over drain flow mitigation, as pesticide concentrations and short-term loads are typically higher for surface runoff events. In addition, erosion control is of utmost concern for farmers. Therefore, no-till should be discouraged on a field only if:*

- Surface runoff is not an issue (which usually is of top priority)
- Drain flow transfer via macropores must be mitigated for pesticides applied to this field.”

6. Grow cover crops

Mottes et al. (2014) describe ground cover as a key property affecting pesticide transfer processes such as runoff, volatization, and erosion. They especially discuss the interaction between tillage and cover crops. Cover crops are usually less treated with PPPs than cash crops and can therefore give PPPs applied for the previous crop more time to degrade instead of accumulating in the soils. Cassigneul et al. (2015) discuss the influence of the nature and decomposition degree of cover crops on pesticide sorption.

Cover crops contribute to the protection of the soil from atmospheric processes such as rainfall, wind, sun radiation (TOPPS, 2018). This helps increase aggregate stability, soil organic matter content and reduce erosion. It also prevents soils from drying out completely through shading. On the other hand, the increased biological activity promoted by cover crops can lead to more biopores and a higher risk for macropore flow. TOPPS (2018) discuss in detail the agronomic constraints involved with implementing cover crops.

7. Optimise drainage practice

Removing the drains or not maintaining them: the question with the renewal of drainages is whether pesticide pollution will be worse if drainages are abandoned. Drainages indeed help mitigation losses by runoff and erosion. Reichenberger et al. (2007) conclude that subsurface drains are an effective mitigation measure for slowly permeable soils with frequent waterlogging. Such soils can however in general not be used for arable farming without subsurface drainage.

Kladivko et al. (2001) also mention that PPP losses mainly happen through surface runoff. If a drained field is prone to surface runoff, it therefore makes more sense to implement a mitigation measure for runoff that might have a negative effect on losses via drainage, than trying to reduce those losses to drainage. Reichenberger et al. (2007) add that the soil should not be over-drained and that a compromise between runoff and drainage losses has to be found to minimize total loss.

Controlled drainage (Skaggs et al., 2012; Satchithanantham et al., 2014) is an engineered drainage solution that consists in controlling the depth to the water table with additional hydraulic infrastructure such as valves. This way, more water is kept in the soil during the growing season than if the field was conventionally drained. This method could also help respond to the problematic of dry summers by storing water when drainage is not necessary anymore. This offers more soil moisture storage at the start of dry summers. Such an infrastructure, however, is costly and requires large fields or farms to be implemented efficiently.

To our knowledge, there is no experience with controlled drainage in Switzerland to date. In other countries, especially the USA, there is widespread experience in particular regarding the control of nitrate and phosphorus losses (Satchithanantham et al., 2014). For example, Saadat et al. (2018) stated that in an experiment with ten years of data collected from an agricultural drained field in eastern Indiana (U.S.A.), comparing two sets of paired plots with free draining plots, the controlled drainage plots had a statistically significant lower annual drain flow (39% resp. 25%). Nitrate load was also statistically significant lower (43% resp. 26%), while annual soluble reactive phosphorus and total phosphorus loads were not significantly different. These results support this management practice as a reliable system for reducing nitrate loss through subsurface drains, mainly caused by flow reduction. Carstensen et al. (2019) investigated the effectiveness and possibility of using controlled drainage during the drainage season to reduce nutrient losses while growing a winter crop in a temperate climate (Denmark). The three-year study was conducted on four experimental field plots on loamy soil by using a before-after control-impact study design. A raise of the water level of 70cm in the drainage infrastructure was required to significantly elevate groundwater levels and reduce the drain outflow and N and P loss, which decreased by 37 to 54%, 38 to 51%, and 43 to 46%, respectively, relative to conventional drainage levels. Youssef et al. (2018) showed that controlled drainage reduced annual subsurface drainage by 30% and annual N drainage losses by 32%, on average over 48 sites across the U.S. However, the large reductions in drain flow resulted in a large increase in surface runoff, which could increase soil erosion and sediment transport to surface water. Williams et al. (2015) discuss the impact controlled drainage may have on losses via surface runoff.

Canga et al. (2016) discusses the potential of granular drainage filters. However, their focus is rather on the removal of phosphorus. They concluded that "*although the challenges that these facilities need yet to solve, such as hydraulic capacity (low P retention during high flow events), dimensioning criteria, low hydraulic conductivity and clogging for certain grain size fractions, high pH of outlet drainage water for calcareous filters, they are however a promising technology for treating P losses from agricultural drainage water with current P removal efficiency of 54–78%"*. Filters can also be developed as an artificial wetland, like in Bruun et al. (2016) who discuss woodchip-based subsurface constructed wetlands for treating drainage water.

Denitrification bioreactors are often used to reduce nitrate leaching. For example, Husk et al. (2017) demonstrated in an experiment in Quebec, Canada, that denitrification bioreactors, combined with controlled drainage, are an effective in-field technology for nitrogen removal from agricultural subsurface drainage water.
However, we are not aware of any installations of drainage filters or bioreactors to reduce PPP losses in Switzerland.

8. Use water-retention structures

Artificial drainage wetlands: This consists in an artificial (or constructed) wetland at the outlet of a set of drainages. It is a popular mitigation measure in France and research is being carried out to quantify its ability of treating pollutant loads (Tournebize et al., 2015).

Reichenberger et al. (2007) note that their effectivity is limited with low and medium sorbing PPPs. Gregoire et al. (2009) discuss the various ways wetlands contribute to pesticide degradation. They define bioremediation as reducing the mobility of PPPs and transforming them into nontoxic chemicals by biological processes using plants and microorganisms. They also discuss the efficiency of biomass beds, which are a constructed accumulation of organic material to treat polluted effluents.
Tournebize et al. (2017) note that adsorption traps pesticide from the water phase, giving secondary importance to other processes such as plant uptake, hydrolysis or photolysis. Living vegetation and litter provide an additional source of organic matter, which helps eliminating pollutants. The efficiency of biological mitigation measures is strongly dependent on hydraulic residence time. They further mention the risk of N_2O emissions and the possible accumulation of PPP metabolites or bound residues in constructed wetlands.
Gregoire et al. (2009) discuss how some pesticides might desorb in the second year and how long-term studies are therefore important to fully understand the potential of some biological mitigation measures. In a comprehensive review, Stottmeister et al. (2003) discuss many aspects of PPP degradation in wetlands and other biological mitigation measures. For example, some PPPs are too polar to adsorb well onto roots. Conversely, some PPPs are highly hydrophobic and are only adsorbed at the root surface without being absorbed by plants. We could not find examples from Switzerland in the literature.

9. Optimise irrigation practices

Irrigation should be limited to necessity, to not activate drains, especially if PPPs have been applied shortly before. Therefore, it is important to take soil water content, crop water requirements and the soil water-holding capacity into account to identify appropriate irrigation. This is rarely done in Switzerland and there is room for improvement, but the immediate potential is small compared to the total drained agricultural area.

10. Biochar application

Khorram et al. (2016) discuss the potential of biochar to remediate soils contaminated by PPPs: *"Biochar has demonstrated a clear and prominent potential to remediate pesticide-contaminated soils through the following: (1) increasing adsorption capacity for pesticides; (2) decreasing desorption and mobility of pesticides in soil layers; (3) decreasing bioavailability of pesticides in soil pore water, which is considered the bioavailable fraction for soil organisms; (4) improving soil microbial activity by providing essential nutrients; and (5)*

improving soil physicochemical properties such as pH, CEC, and water holding capacity." "Biochar has a strong sorption capacity for pesticides, and it seems that biochar amendment can lead to an accumulation of pesticide residues in the amended soils, which could act as a new source of pollution. Therefore, the long-term environmental fate of sequestered pesticides must be evaluated."
The well-cited review by Ahmad et al. (2014) discuss the potential of biochar as a sorbent for contaminant management in soil and water.

11. Paludiculture

Replacing any crop, which may have detrimental effects on drainage loss by a more favorable crop is another avenue. Paludiculture is one option that is popular in Germany. Wichmann et al. (2020) discusses the potential of paludiculture from a central-European perspective. He focuses on wetland forestry for bio-energy purposes. This method has the added benefit of restoring carbon levels in drained organic soils. However, it is a specialized type of agricultural practice that is limited to peat soils as well as requiring specific knowledge and machinery.

12. Rice production

Rice production is an option with which some farmers in Switzerland are starting to experiment (Jacot et al., 2018). However, the Swiss climate remains quite challenging for this crop, and the specific local knowledge is low. This will therefore remain a minor option for the time being.

13. Agroforestry

In Asia, wetland-based agroforestry is practiced (i.e. Arunachalam et al., 2014). As with rice production, this remains difficult in the Swiss climate and requires specific tools and knowledge that is currently rare in our latitudes (Kay et al., 2019). Currently, 120 ha of agroforestry practice exists in Switzerland (Kay et al., 2019). How much of it is (or was) drained land is unknown. Additionally it remains to be shown, whether taproot trees could help with infiltration through clayey soil layers.

4.2.2 Best mitigation measures: advice for PPP use on drained land

Optimizing the date of application would intrinsically be the best mitigation measure. It is however rare to have much choice as to when to spray. Fungicides are also more often required in period of wet weather conditions, making their timing optimization rather difficult.

To best specify mitigation measures, a map of areas most concerned by PPP losses via drainage would help. Is there for example a relationship between the amount of drained areas and the measured PPP concentrations in small catchments? This question cannot be answered yet. Drainage maps and a more detailed understanding of the possible point losses in the NAWA SPEZ catchments would be helpful. The data density is currently probably too low to come up with rigorous conclusions.

4.3 Mitigation measures within the PPP regulation framework

4.3.1 Existing regulations regarding losses via runoff and erosion

The regulations regarding PPP application were strengthened in 2018 to mitigate losses to watercourses via runoff and erosion (instructions regarding those measures are specified in BLW, 2018 and Agridea, 2018). If specified on the pesticide's user manual, suitable measures must be taken to reduce runoff. This applies to all plots with a slope of more than 2%, which are located less than 100 meters from surface water. The risk of runoff is reduced when measures or combinations of measures achieve the required number of points (1 to 4 points).

Section 4.2 stated that most measures that are suitable for reducing PPP losses via leaching, runoff and erosion are also suitable for reducing PPP drainage losses. However, the measures against runoff selected in the regulation process have little or no effect on PPP losses via drainage. Buffer strips of different widths have no positive effects on PPP losses due to drainage. Grassed driving lanes, grassed stripes (min. 3m wide) where runoff is generated, or grassed buffer strips at the edges of the plot, hardly have any reducing effects on PPP losses via drainage. Only the measure requiring a treatment of less than 50% of the area (i.e. belt spraying or partial surface treatment) will lead to a reduction in PPP losses via subsurface drainage. Finally, vegetated buffers near surface draining ditches would reduce the amount of PPP losses to this specific type of drainage infrastructure.

For those reasons, both the assessment methodology (by points) for mitigation measures against runoff and the "Weisungen betreffend der Massnahmen zur Reduktion der Risiken bei der Anwendung von Pflanzenschutzmitteln" (BLW, 2018) cannot be adopted or adapted for drainage. To our knowledge, there are no mitigation measures that are explicitly suitable only for drained areas and that can be recommended specifically for those areas. In our opinion, the only registration-specific measure for PPP on drained land would be prohibiting certain PPPs. Enforcing prohibition specific to drained land would however run into the difficulty of clearly identifying those areas. Despite the Swiss drainage map (Koch and Prasuhn, 2020), the availability of reliable data is still poor. Often, even farmers would not know, whether their land is drained or not. As best option, we consider the development of location-dependent measures and generally, the improvement of best management practices.

4.3.2 Potentially counter-productive measures used against runoff and erosion

Some measures against erosion such as transverse dams in potato production will have the effect of locally increasing infiltration (Lemann et al., 2019, Prasuhn et al., 2017) and therefore increasing the risk of pesticide losses via drainage, especially if the soil is prone to preferential flow.

The effect of no-till on PPP losses via drainage is difficult to generalize but tends to increase losses as discussed in Sections 2.8 and 4.2. However, on land prone to runoff and erosion, the reduction in losses via those pathways tends to outweigh the potential risk of increased drainage losses. Therefore, no-till should still be promoted on plots that are susceptible to runoff, whereas care should be taken on land that is flat and prone to be drained.

4.4 Potential effects on climate change on pesticide losses via drainage

With increasing temperatures, it is likely that more winter crops will be sown, which will increase the application of pesticides in autumn. If increased precipitation in autumn happens as predicted by the latest climate models (i.e. changing frequency, intensity and higher variability of precipitation events; see NCCS, 2018), this could lead to increased pesticide leaching in autumn. Higher temperatures will however increase degradation rates, especially in spring. On the other hand, if pesticides applied in spring are exposed to drier conditions during spring and summer, bacterial degradation may be slower. In addition, the soil organic carbon cycle will accelerate, which may lead to a decrease in SOC contents and consequently less soil adsorption. More extreme precipitation events in summer will lead to higher risk of runoff, erosion and preferential flow (Bloomfield et al., 2006). Overall, both transport and fate processes may be affected by climate change with competing impacts.

The “Water quality ecological status” report (Benateau et al., 2019) explains that dry summers followed by wet winters would lead to decreased leaching in summer followed by increased leaching in winter. They present the example of nitrate in 2003. Many PPPs significantly degrade within 6 months, making this phenomenon probably less acute for pesticides and only for those with slow degradation properties. Overall, this may lead to more impact of long-lived PPPs and less impact of short-lived compounds. These relationships are illustrated in Figure 26.

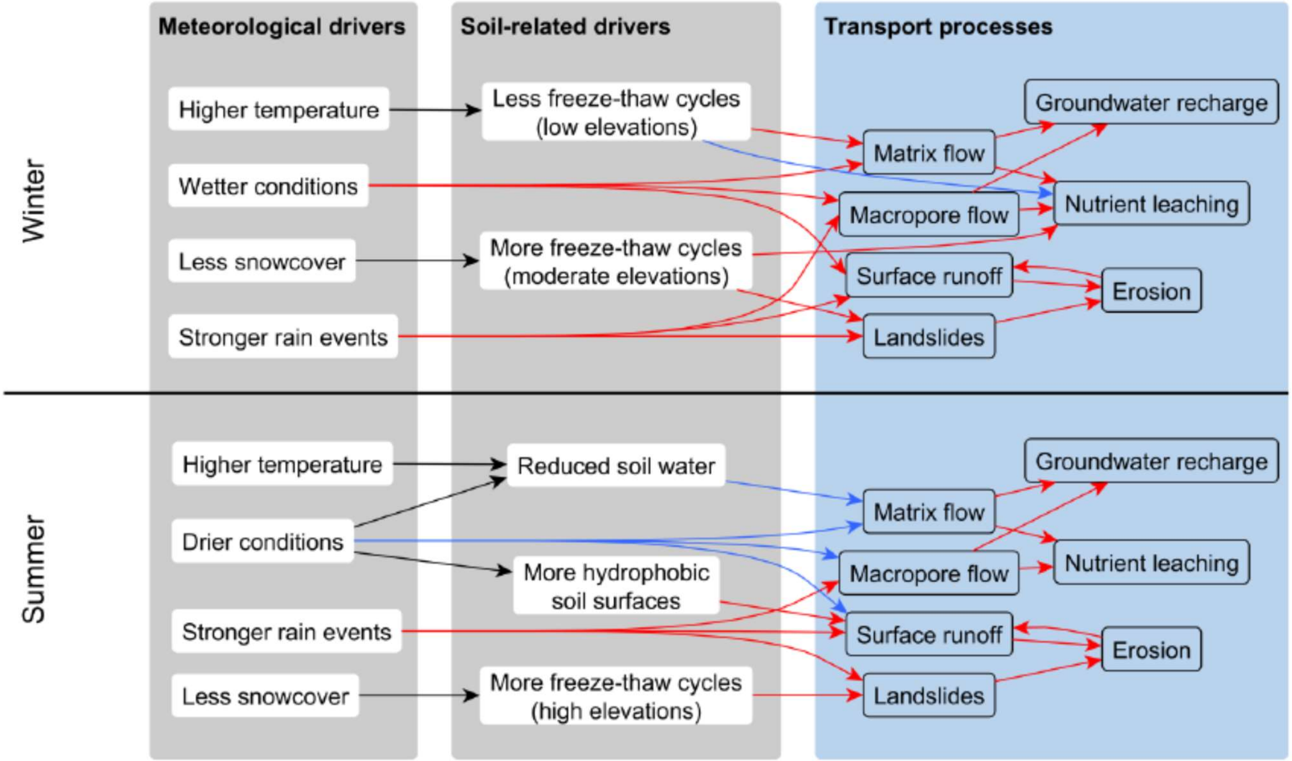

Figure 26: Conceptual diagram linking the drivers (left and middle panels) to their positive (red arrows) or negative (blue arrows) impacts on transport processes (from Benateau et al., 2019).

5 Conclusions and outlook

We have created a conceptual model in form of a table and a flowchart. It is based on an extensive literature review, including data from Swiss experiments and shows the interactions between the most important processes and parameters affecting PPP losses through drainage. However, it is difficult to illustrate the complex processes in a comprehensive while simple way. There are numerous other approaches in the literature to illustrate the transport processes driving PPP losses to surface water and groundwater. Therefore, we compiled additional flowcharts and conceptual models in the Appendix (A.1).

It is well documented that PPP losses via drainage can be important transport pathways in Switzerland with regard to PPP- concentrations and load (Doppler et al., 2012; Doppler et al., 2014a; Leu et al. 2004b; Leu et al., 2005). However, it was also shown that losses from drained fields can be very low (Gomides Freitas et al., 2008). The reason for this variability is likely due to the interactions with other loss pathways and the hydro(geo)logical context. Individual processes are reasonably well understood, but the various interactions between parameters in heterogeneous soils and farm contexts, such as drainage design, crops, tillage practices and PPP use make it difficult to disentangle the quantitative relevance of the different interlinked processes.

Therefore, measurement of PPP concentrations in surface waters are usually not sufficient to quantify losses via drainage, because runoff, erosion and shortcut losses are often more important and occur at the same time. According to our findings, there is only one study in Switzerland (Wettstein et al., 2016) in which PPP losses via drainage were measured in detail under field conditions. Although the general understanding of PPP losses via drainage is relatively good, site-specific conditions ultimately dominate PPP losses. New experimental studies of drainage systems would therefore be helpful in order to better assess whether the EXPOSIT registration model (developed in Germany) correctly reflects worst-case situations in Switzerland. Experimental studies should make sure that all flow pathways could be differentiated. Application data of PPP and agricultural practices (crop types, cultivation methods) should be recorded. Detailed soil and hydrological information is needed at high temporal resolution to understand processes driving peak PPP losses via drainage, especially in relationship with losses via runoff and erosion.

The soils in are relatively homogeneous in the lowlands, which does not allow for much differentiation based on soil properties. In addition to the adsorption and degradation properties of PPPs, the more important variables are weather conditions, the depth to drainage and agricultural practices. However, peak losses via drainage are strongly influenced by the extent of preferential flow and therefore depend less on PPP properties compared to leaching or runoff and erosion losses. In Switzerland, most agricultural soils are loams, which are prone to macropore flow via biopores, and in some cases shrinkage cracks. In combination with the high rainfall amounts and frequent heavy rainfall events in Switzerland, this results in an overall high risk of PPP losses via drainage systems. As approximately 22% of the utilized agricultural area in Switzerland is drained (Koch and Prasuhn, 2020), we conclude that drainage is an important factor for PPP losses in agricultural soils and should not be neglected.

The catalogue of mitigation measures presented by TOPPS (2018) is comprehensive, well documented and suitable for application in Switzerland. Mitigation measures are mostly common with those recommended against leaching, runoff and erosion. In addition, most of them are already part of the “proof of ecological performance” in Switzerland, leaving little room for improvement. We listed additional measures, which are, however, often difficult to implement in Switzerland for climatic or topographic reasons.

No-till is a measure that is being promoted for its positive impact on soil health as well as reduction of PPP losses via runoff. The effect of no-till on PPP losses via drainage is difficult to generalize but can lead to increased losses. However, on land prone to runoff and erosion, the reduction in losses via those pathways tends to outweigh the potential risk of increased drainage losses. Therefore, we suggest that no-till should still be promoted on plots that are susceptible to runoff, but not necessarily on land that is flat and prone to be drained. This should be considered in the risk management of PPP losses via runoff in Switzerland.

Among the many inter-related variables affecting PPP losses via drainage, the key variable remains the time between application and the first intense rain event. This makes the application date theoretically the most important mitigation measure. In practice, the scope for farmers is, however, limited because of several constraints such as limited time windows according to the crop stage, frequent rainfall events, or logistic reasons. We advise farmers working on drained land, in addition to agricultural best management practices, not to apply PPPs if a strong rain event or storm is forecasted in the next few days or if the drains are already active. At the farm scale, flat areas that concentrate surface runoff may be drained and act as infiltration “hotspots” and thus mitigation measures should be attempted in priority there.

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7 APPENDIX

7.1 A.1 Key process diagrams from the literature

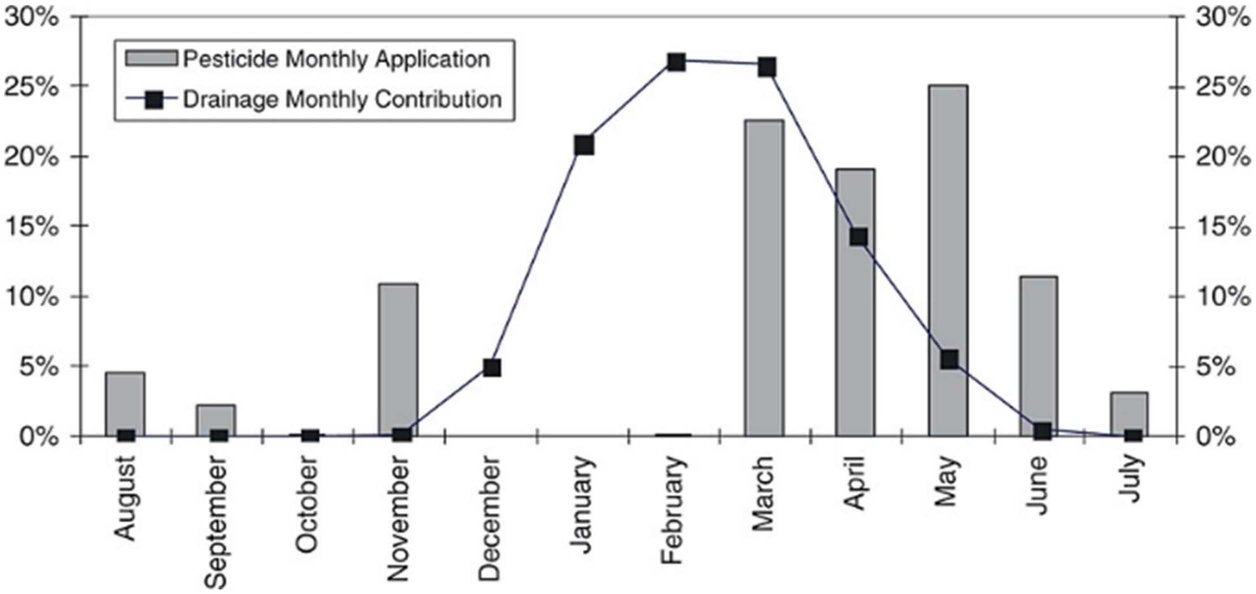
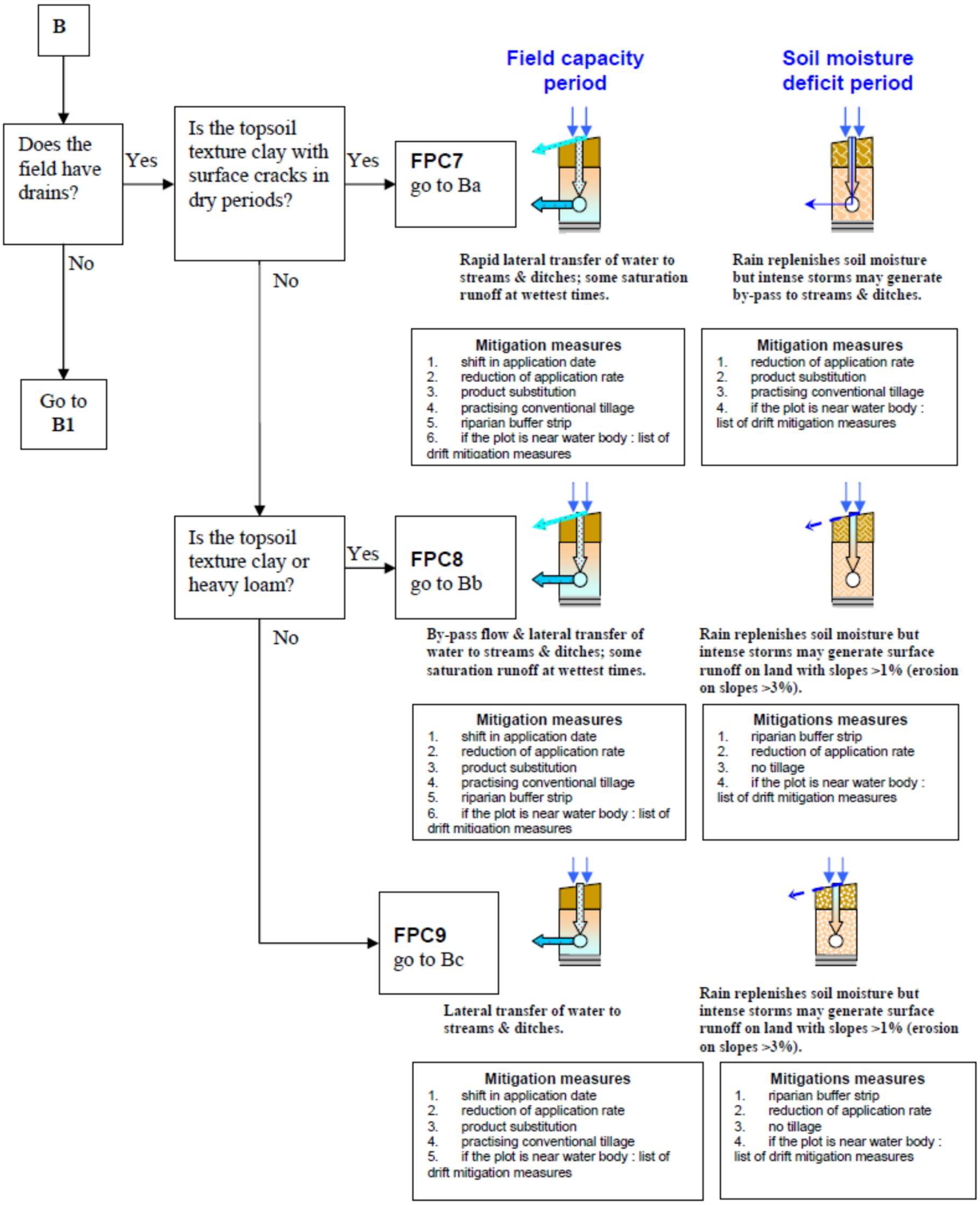


Figure A.1: Seasonal dynamics of pesticide application and drainage contribution to total discharge (Tournebize et al., 2012).



Rapid lateral transfer of water to streams & ditches; some saturation runoff at wettest times.

Rain replenishes soil moisture but intense storms may generate by-pass to streams & ditches.

Mitigation measures
1. shift in application date
2. reduction of application rate
3. product substitution
4. practising conventional tillage
5. riparian buffer strip
6. if the plot is near water body : list of drift mitigation measures

Mitigation measures
1. reduction of application rate
2. product substitution
3. practising conventional tillage
4. if the plot is near water body : list of drift mitigation measures

By-pass flow & lateral transfer of water to streams & ditches; some saturation runoff at wettest times.

Rain replenishes soil moisture but intense storms may generate surface runoff on land with slopes >1% (erosion on slopes >3%).

Mitigation measures
1. shift in application date
2. reduction of application rate
3. product substitution
4. practising conventional tillage
5. riparian buffer strip
6. if the plot is near water body : list of drift mitigation measures

Mitigations measures
1. riparian buffer strip
2. reduction of application rate
3. no tillage
4. if the plot is near water body : list of drift mitigation measures

Lateral transfer of water to streams & ditches.

Rain replenishes soil moisture but intense storms may generate surface runoff on land with slopes >1% (erosion on slopes >3%).

Mitigation measures
1. shift in application date
2. reduction of application rate
3. product substitution
4. practising conventional tillage
5. if the plot is near water body : list of drift mitigation measures

Mitigations measures
1. riparian buffer strip
2. reduction of application rate
3. no tillage
4. if the plot is near water body : list of drift mitigation measures

Figure A.2: FOOTPRINT FPCs linked to specific mitigation measures (Reichenberger et al., 2008).

The different options have been called “FPC Flow Pathway Category”. “The FPCs have mainly been derived from the CORPEN conceptual hydrological diagrams with aspects of the HOST diagrams included. There are FPCs for each of 7 soil parent material types and, within each type, different FPCs depending on the presence or absence of artificial drainage systems, topsoil textural characteristics and soil water regimes. The associated, FPC- and season-specific mitigation measures that are recommended to the user were derived during FOOTPRINT activity 3.1.”

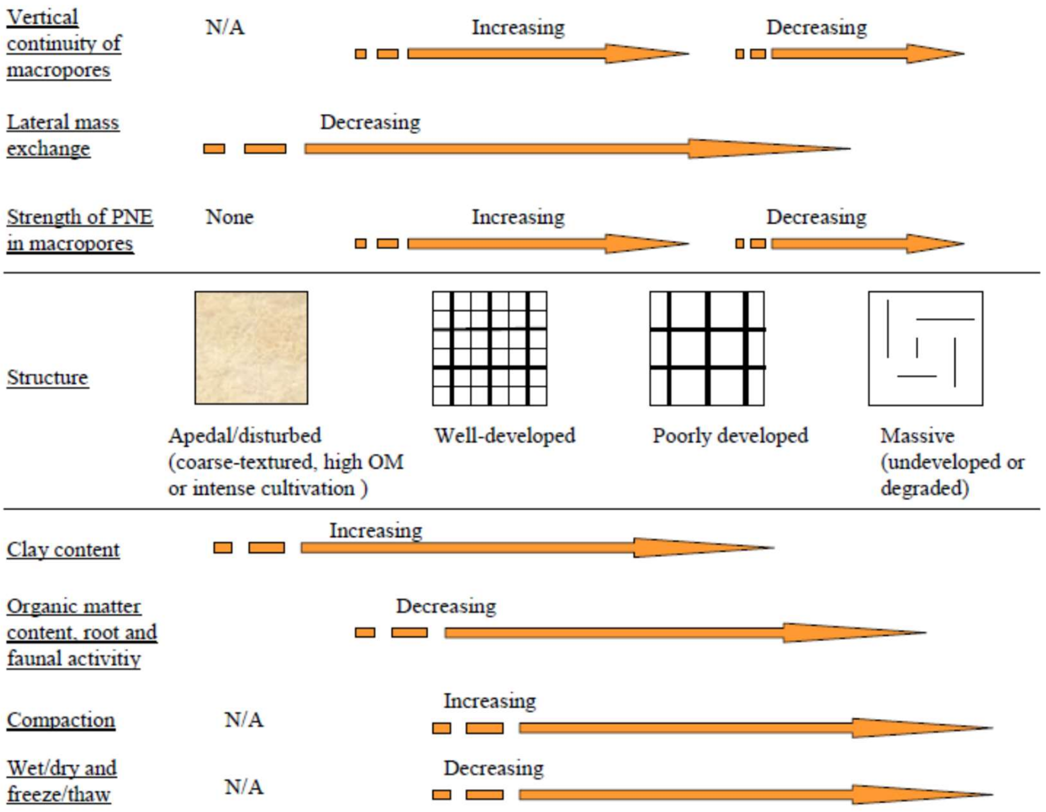


Figure 1. Conceptual model of macropore flow and transport.

The center of the diagram shows for illustrative purposes four classes of structural development. The bottom third of the diagram shows how the various factors of structure formation and degradation influence structural development, while the top third of the diagram illustrates the probable consequences for non-equilibrium water flow and solute transport in macropores (PNE = physical non-equilibrium, OM = organic matter).

Figure A.3: From Jarvis et al., 2012.

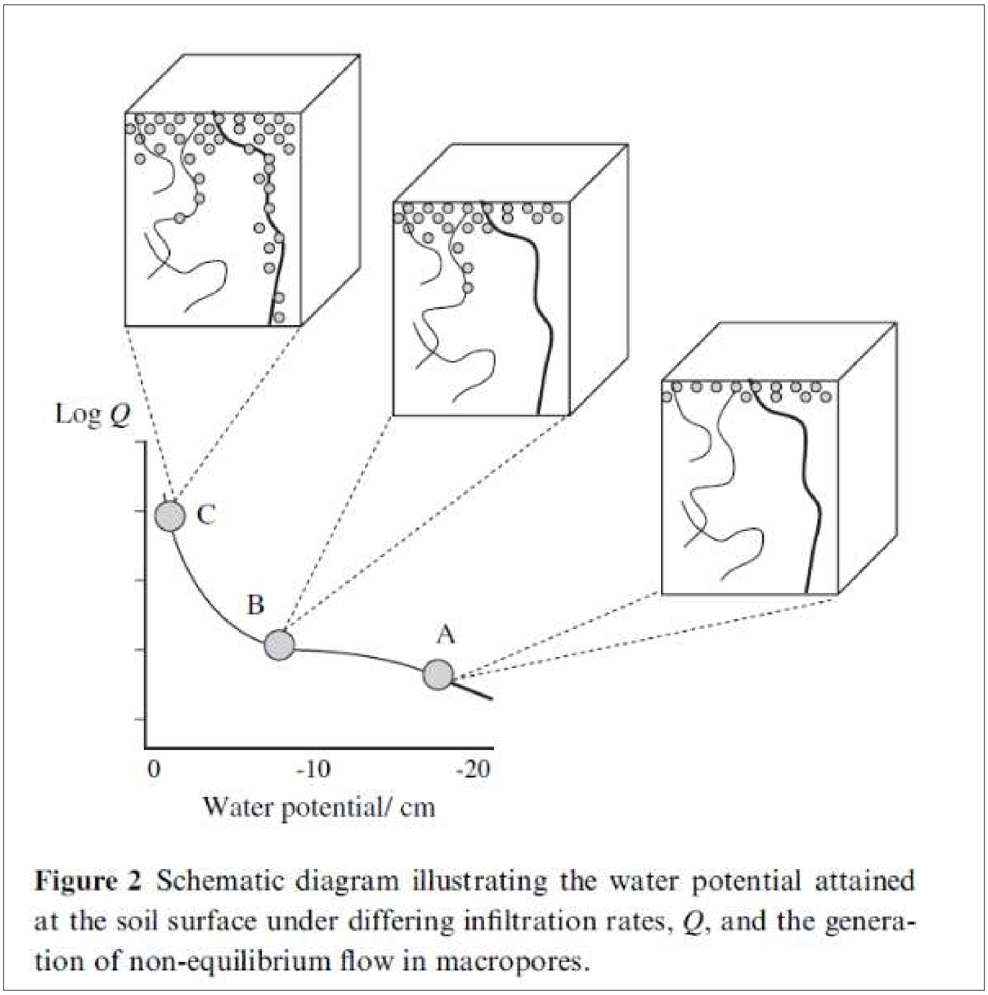


Figure 2 Schematic diagram illustrating the water potential attained at the soil surface under differing infiltration rates, Q, and the generation of non-equilibrium flow in macropores.

Figure A.4: From Jarvis, 2007.

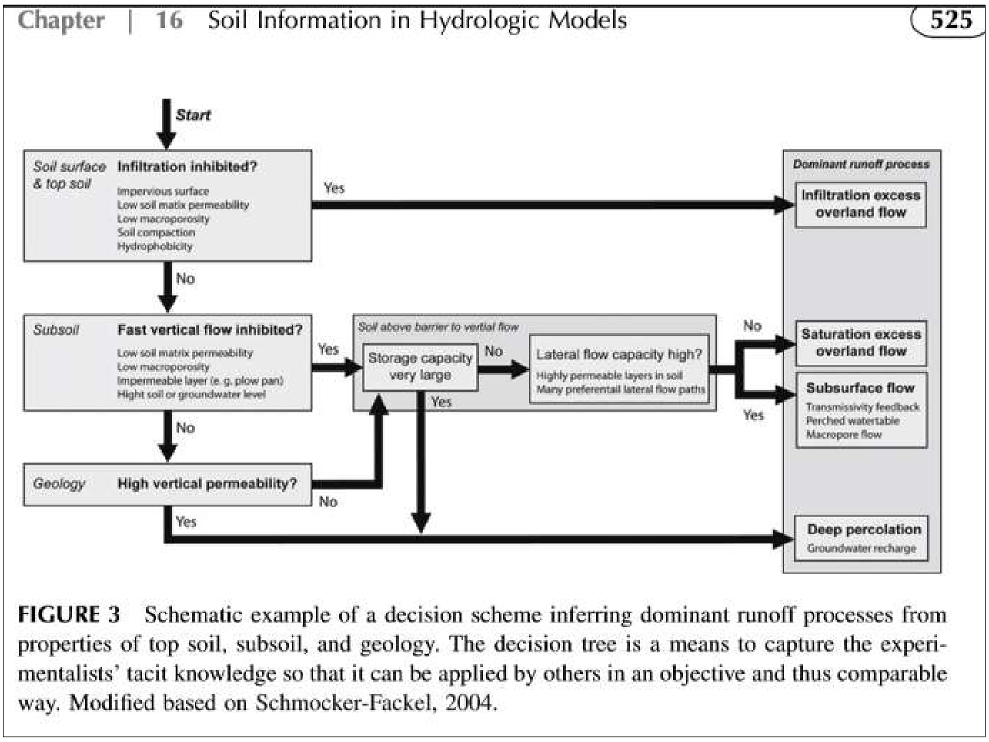


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FIGURE 3 Schematic example of a decision scheme inferring dominant runoff processes from properties of top soil, subsoil, and geology. The decision tree is a means to capture the experimentalists' tacit knowledge so that it can be applied by others in an objective and thus comparable way. Modified based on Schmocker-Fackel, 2004.

Figure A.5: Simple decision tree relation to Preferential Flow and deep percolation (Rinderer 2015).

This decision helps understanding the dominant runoff processes based on top soil, subsoil and geological properties. It can be used during field surveys to understand a catchment as a whole.

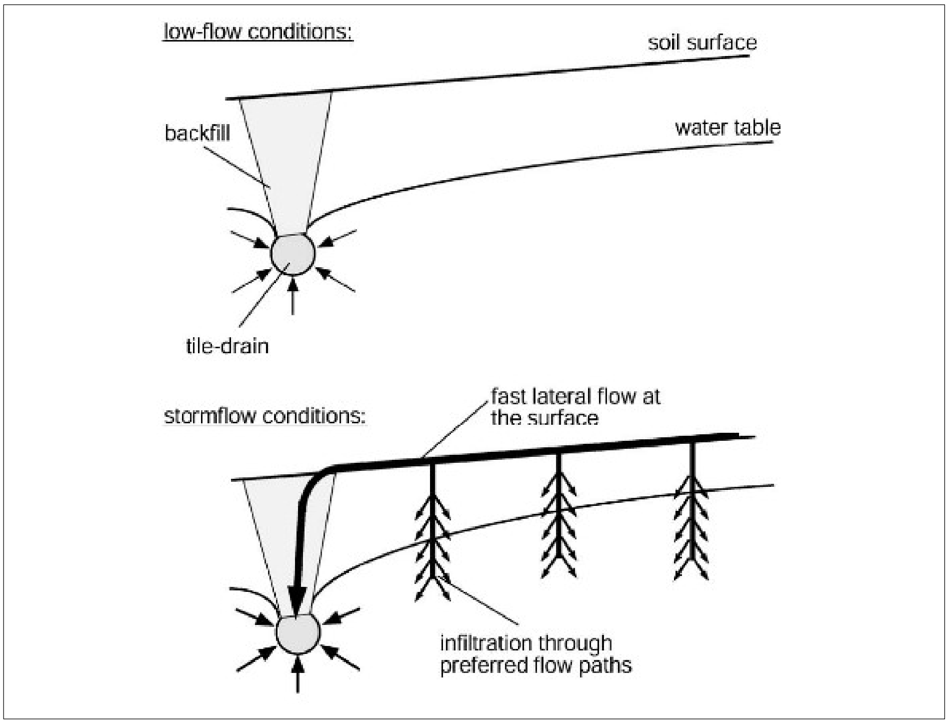


Figure A.6: Conceptual model of the flow paths for the fast transport into a tile drain in a weakly structured loamy soil (Stamm et al., 2002).

Stamm et al. (2002) describe the dynamics of a drained grassland in Switzerland. During low-flow conditions, the drain is mainly fed by matrix flow thanks to the higher water table. During stormflow conditions, fast lateral flow builds up at the surface. Some of it infiltrates through preferential flow paths and it then led laterally to the drain. The rest infiltrates in the more permeable backfill of the trench.

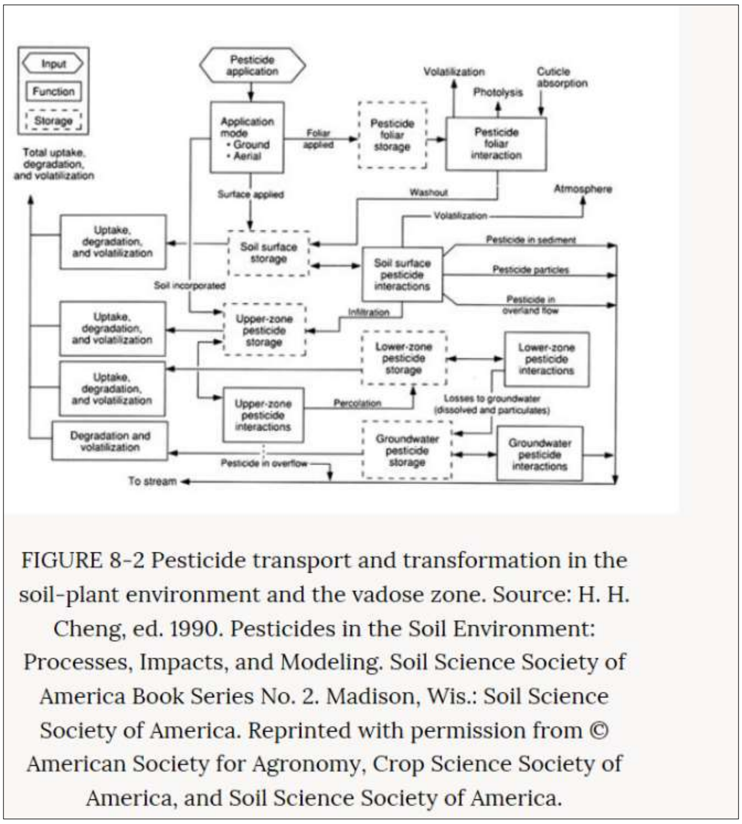


FIGURE 8-2 Pesticide transport and transformation in the soil-plant environment and the vadose zone. Source: H. H. Cheng, ed. 1990. Pesticides in the Soil Environment: Processes, Impacts, and Modeling. Soil Science Society of America Book Series No. 2. Madison, Wis.: Soil Science Society of America. Reprinted with permission from © American Society for Agronomy, Crop Science Society of America, and Soil Science Society of America.

Figure A.7: Pesticides in the soil environment: processes, impacts and modeling, 1990 (https://www.nap.edu/read/2132/chapter/12#315).

This flowchart focuses on the fate of PPP, putting into evidence storages and processes. The main storages are leaves, soil surface, upper- and lower-zone soil storage as well as groundwater storage.

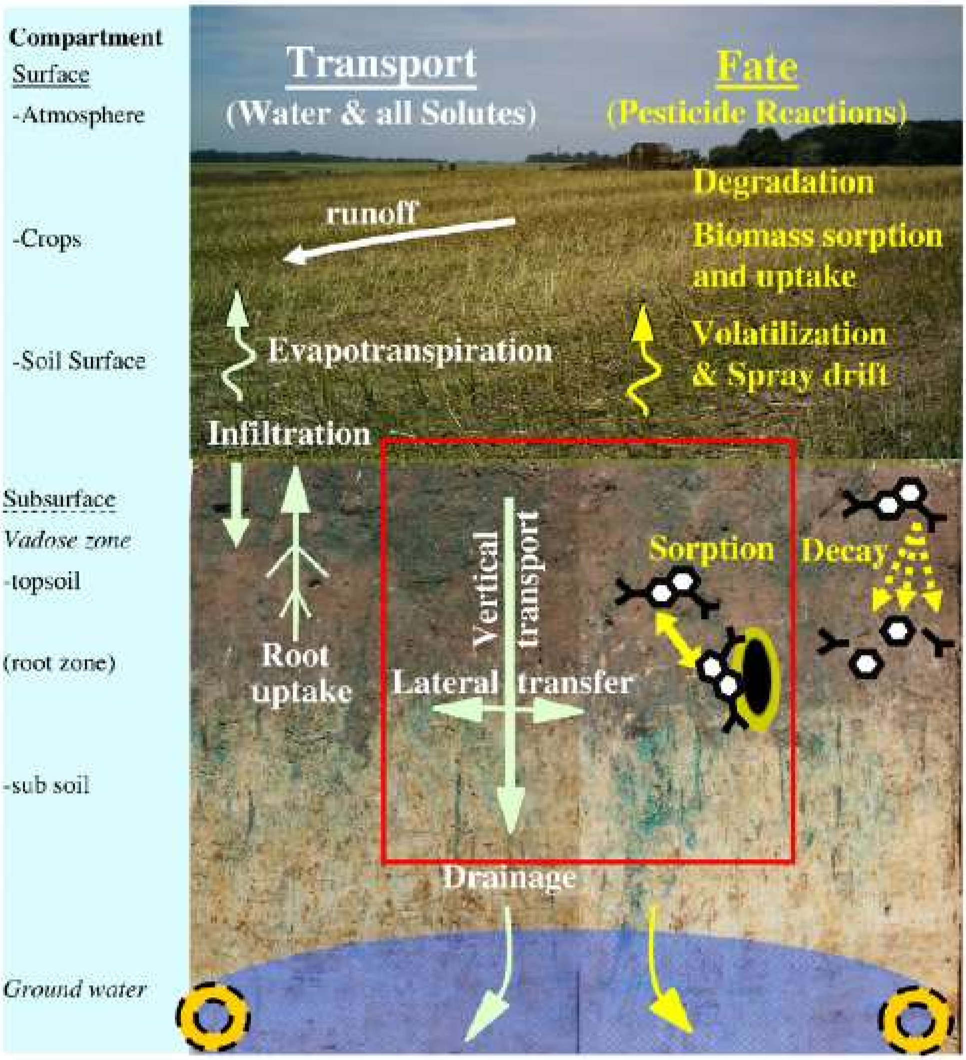
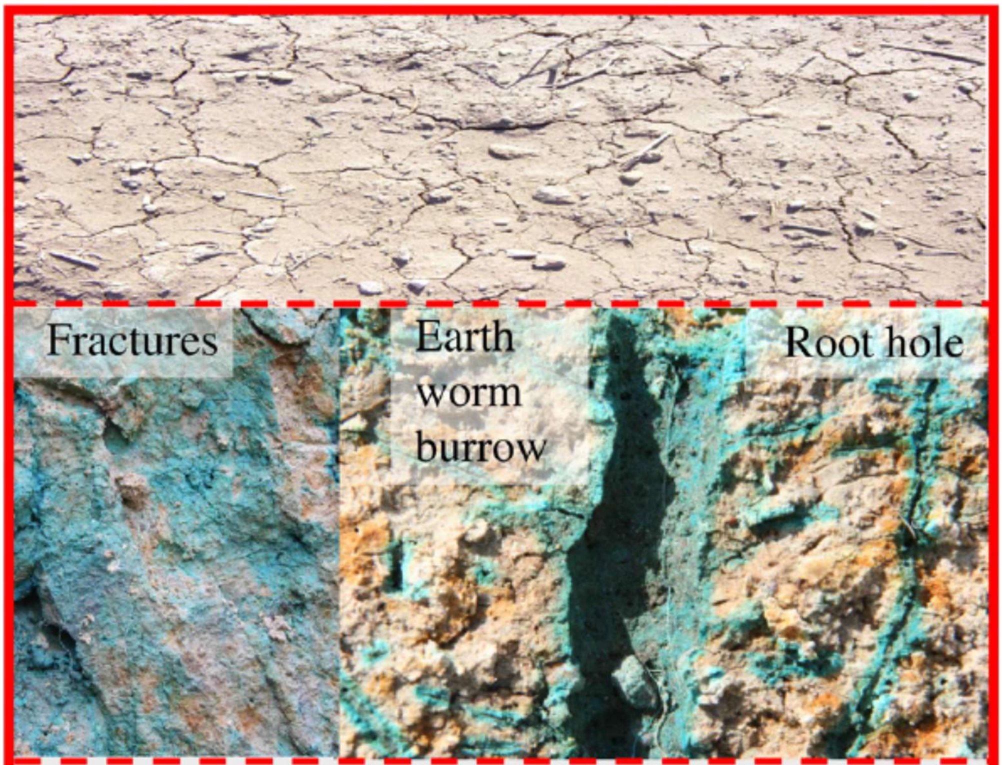


Fig. 1. Principal processes governing pesticide transport and fate in agricultural structured soil systems. The central frame is explained in Fig. 2.

Figure A.8: A review of model applications for structured soils – pesticide transport (Köhne et al. 2009b).

The figure above presents the various hydrological and pesticide fate processes influencing losses to drainage. A the soil surface, volitization, spray drift, biomass sorption and uptake as well photo- and microbial degradation influence the fate of pesticides. Water can infiltrate through the soil matrix or via macropores. There will always be some lateral exchange of solutes. This exchange can be substantial if a saturated macropore is surrounded by a rather permeable and dry matrix. This will lead to the temporary immobilization to pesticides. Degradation rates are however typically much slower in the subsoil so that this process might decrease peak leaching concentrations but not the overall quantity leached over time.



Soil characteristics	Extent of preferential flow	Typical dye pattern
Macropores in low-permeability matrix	High (low transfer)	
Mixed-permeability matrix and macropores	Medium (mixed transfer)	
Macropores in high-permeability matrix	Low (high transfer)	
Homogeneous soil	Uniform flow	

Figure A.9: A review of model applications for structured soils – pesticide transport (Köhne et al. 2009b).

The second figure, which details the red quadrant, shows different types of macropore flow and the interaction with the matrix. The highest extent of preferential flow, with macropores in a low-permeability matrix, will be worst-case for peak PPP losses via drainage. A homogeneous soil will present the least risk with regard to peak PPP losses. Overall losses do not necessarily follow these patterns as they will depend on rainfall intensity, the hydraulic conductivity through the matrix as well as degradation and sorption properties of the chemical.

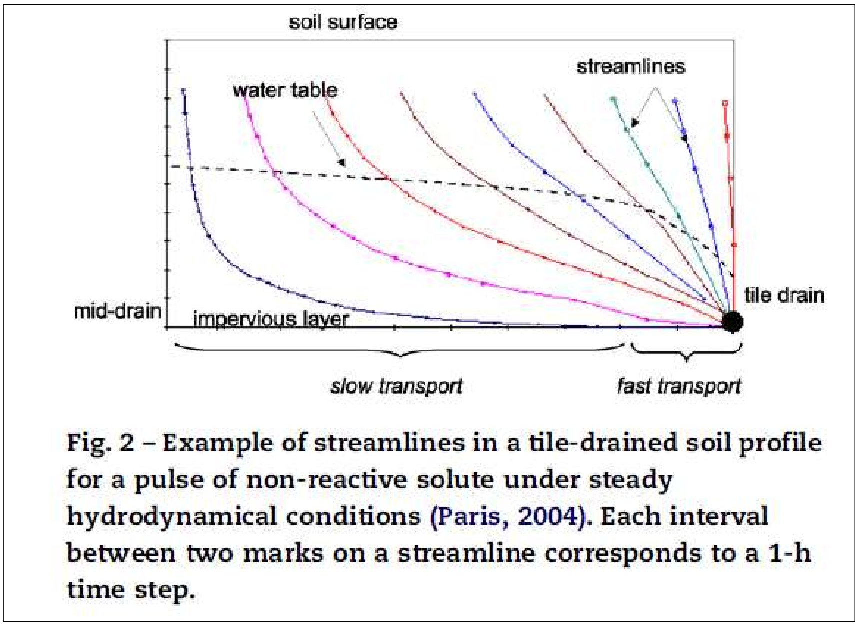


Fig. 2 – Example of streamlines in a tile-drained soil profile for a pulse of non-reactive solute under steady hydrodynamical conditions (Paris, 2004). Each interval between two marks on a streamline corresponds to a 1-h time step.

Figure A.10: A simplified modelling approach for pesticide transport in a tile-drained field (Branger et at., 2009).

Close to the drain, high hydraulic gradients generate fast radial flow in both saturated and unsaturated zones, whereas velocities are low at mid-drain. The figure shows that not only travel distances, but also travel times are much shorter close to the drain. In addition, backfill surrounding the tile drain can sometimes present a higher saturated hydraulic conductivity, increasing the non-linearity of this distance relationship.

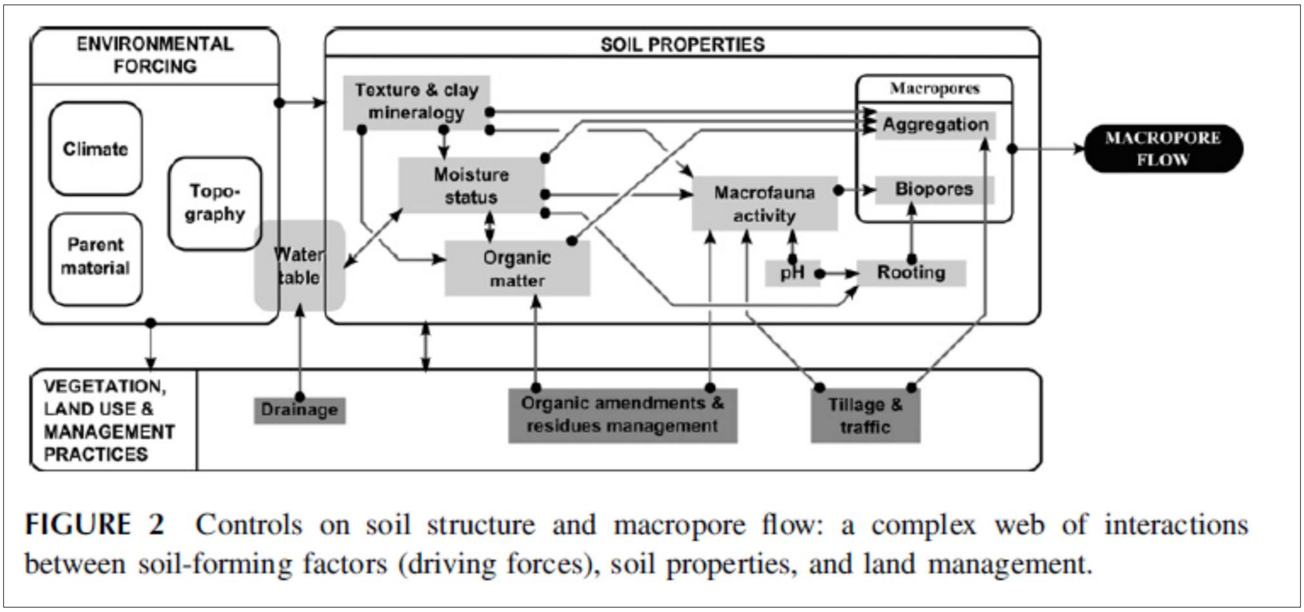


FIGURE 2 Controls on soil structure and macropore flow: a complex web of interactions between soil-forming factors (driving forces), soil properties, and land management.

Figure A.11: From Jarvis et al. (2012).

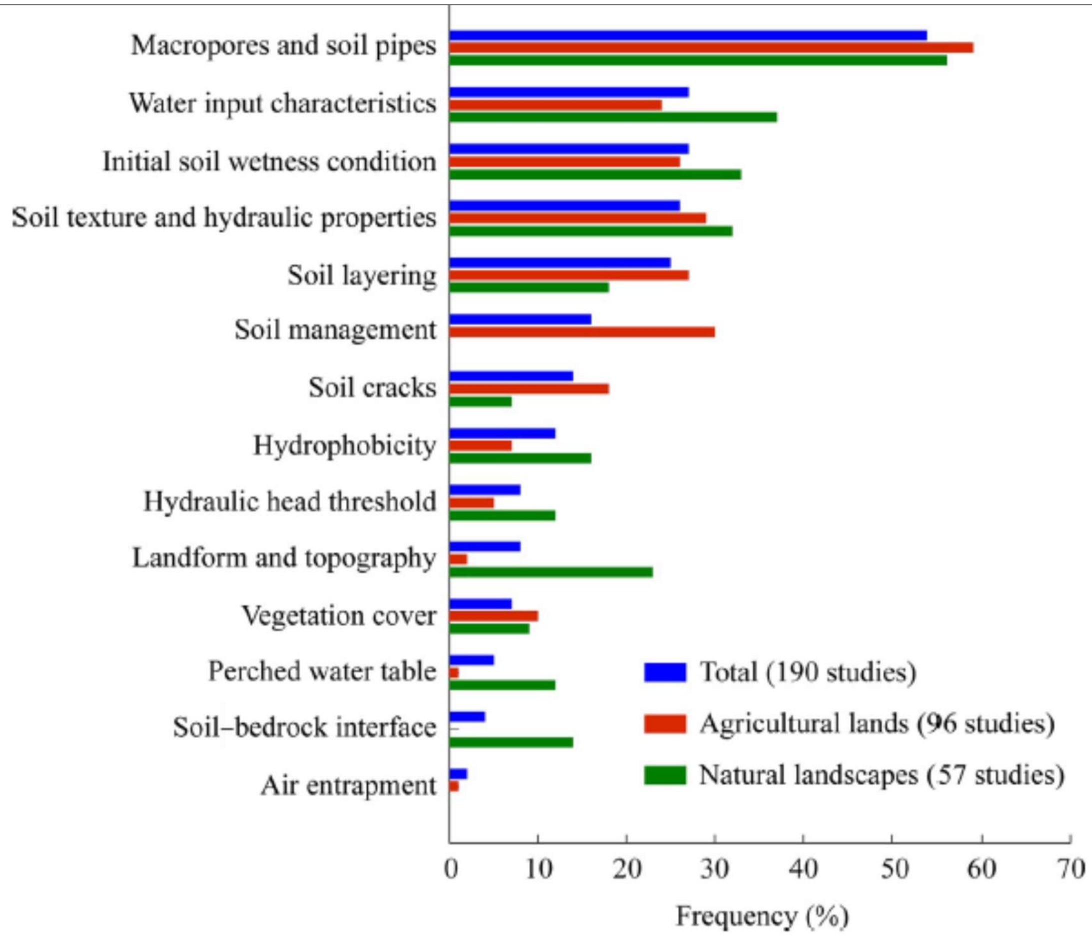


Fig. 2 Most frequently identified factors that control preferential flow in soils across various soils and landscapes. The frequency of each factor is calculated as the ratio of the number of papers that suggest such a factor as a control of preferential flow to the number of total papers investigated. *Blue bars* represent results from all of the 190 selected case studies. *Red bars* are results from 96 studies conducted on agricultural soils. *Green bars* are results from 57 studies conducted in natural landscapes (nonagriculture). Each dominant factor is discussed in the text. Note that not all control factors are of a comparable category.

Figure A.12: From Guo and Lin (2018).

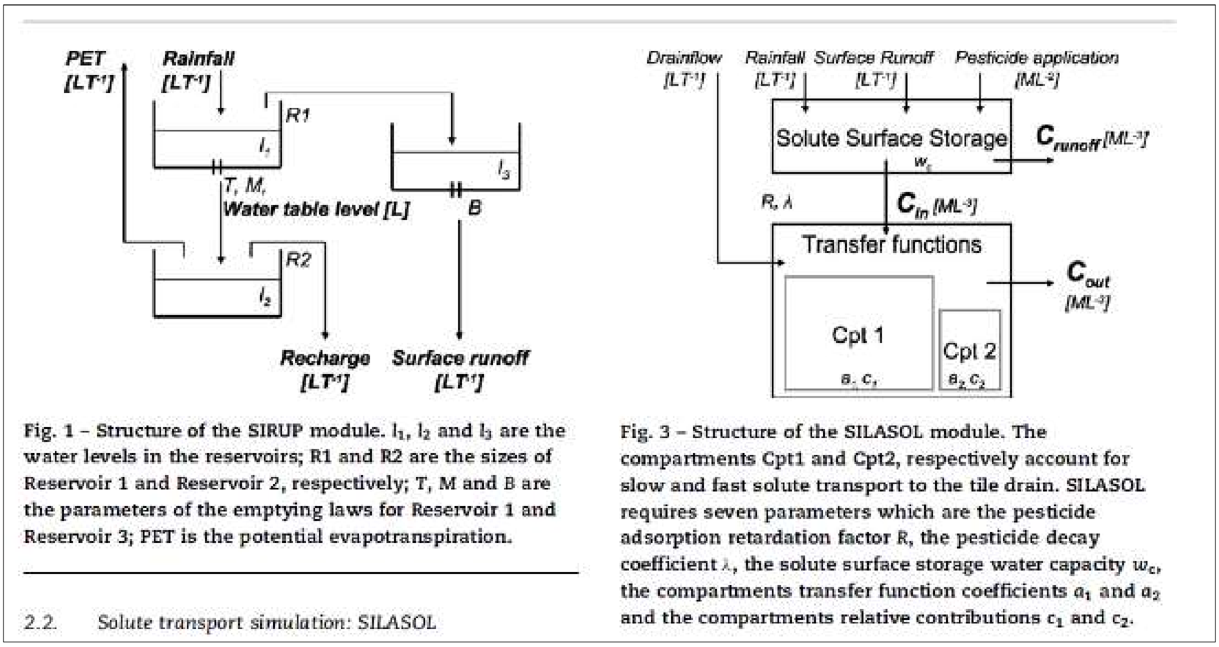


Fig. 1 – Structure of the SIRUP module. l_1, l_2 and l_3 are the water levels in the reservoirs; R1 and R2 are the sizes of Reservoir 1 and Reservoir 2, respectively; T, M and B are the parameters of the emptying laws for Reservoir 1 and Reservoir 3; PET is the potential evapotranspiration.

2.2. Solute transport simulation: SILASOL

Fig. 3 – Structure of the SILASOL module. The compartments Cpt1 and Cpt2, respectively account for slow and fast solute transport to the tile drain. SILASOL requires seven parameters which are the pesticide adsorption retardation factor R, the pesticide decay coefficient λ, the solute surface storage water capacity w_c, the compartments transfer function coefficients a_1 and a_2 and the compartments relative contributions c_1 and c_2.

Figure A.13: A simplified modelling approach for pesticide transport in a tile-drained field: The PESTDRAIN model (Branger et al. 2009).

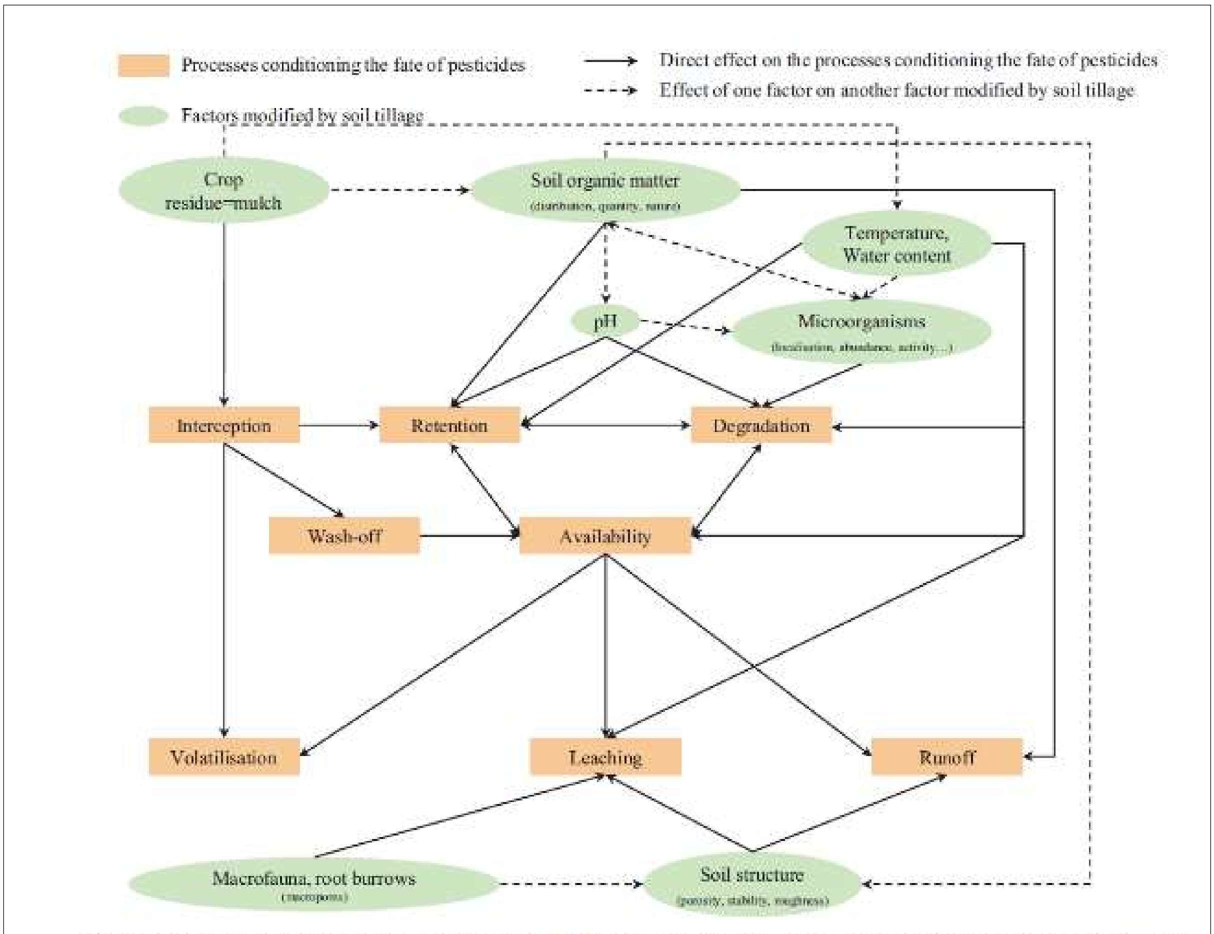


Figure 4. Relationships between the processes conditioning the fate of pesticides in soils, water and air and the soil factors modified by tillage operations.

Figure A.14: Tillage management effects on pesticide fate in soils – a review (Alletto et al., 2010).

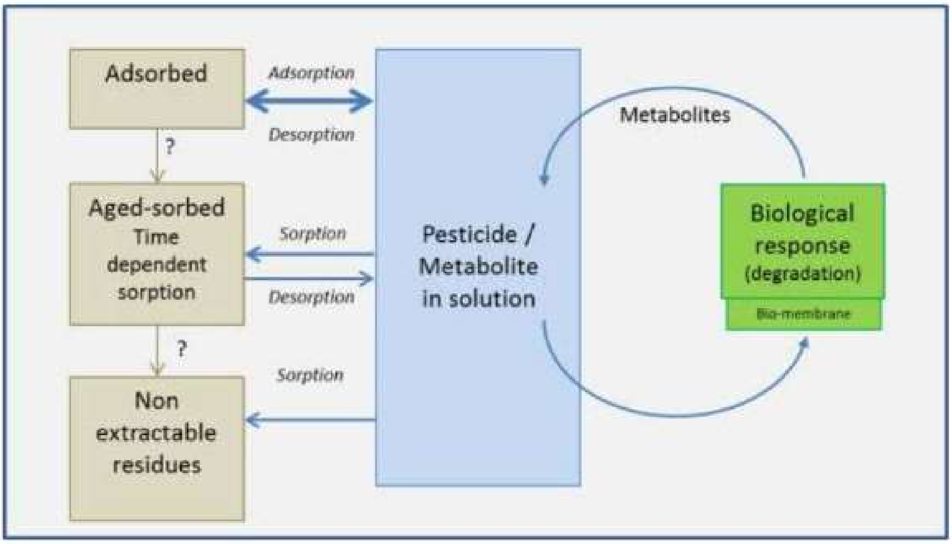


Figure 1: Simplified conceptual model of adsorption/sorption of pesticides and their metabolites to soils. Figure prepared by the PPR WG.

Figure A.15: From EFSA (2015).

Climatic factors influencing leaching and transport of pesticides

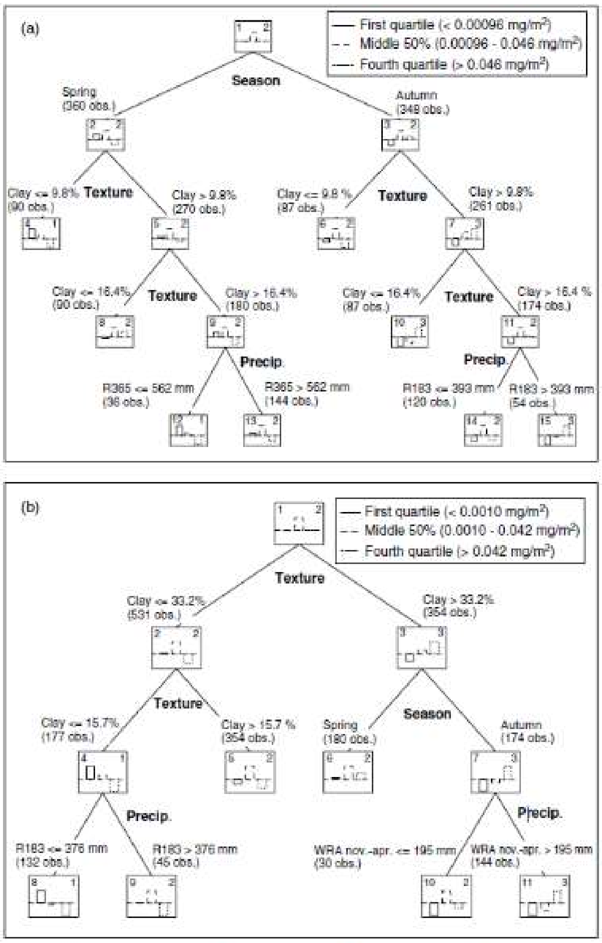


Figure 1. Classification tree analysis of cumulative solute loss for (a) leaching and (b) drainage scenarios. Tree nodes are indicated by boxes, with the node number in the upper left-hand corner of the box. The estimated contamination status of a node (1 = first-quartile pesticide loss, 2 = middle 50% of losses, 3 = fourth-quartile loss) is shown in the upper right-hand corner of the box and is based on the class with the largest number of observations at the node. The vertical bars indicate proportional changes in class members (MACRO predictions of pesticide loss) at a particular child node, compared with the parent node. The left-hand bar corresponds to the first-quartile pesticide loss, the middle bar corresponds to the middle 50% of the data and the right-hand bar corresponds to the fourth-quartile loss. For example, in 1b the bars indicate that node 3, which is estimated to have fourth-quartile pesticide loss, has a higher proportion of fourth-quartile members relative to the other two classes in comparison with the parent node (1).

Figure A.16: Identification of key climatic factors regulating the transport of pesticide in leaching and to tile drains (Nolan et al., 2008).

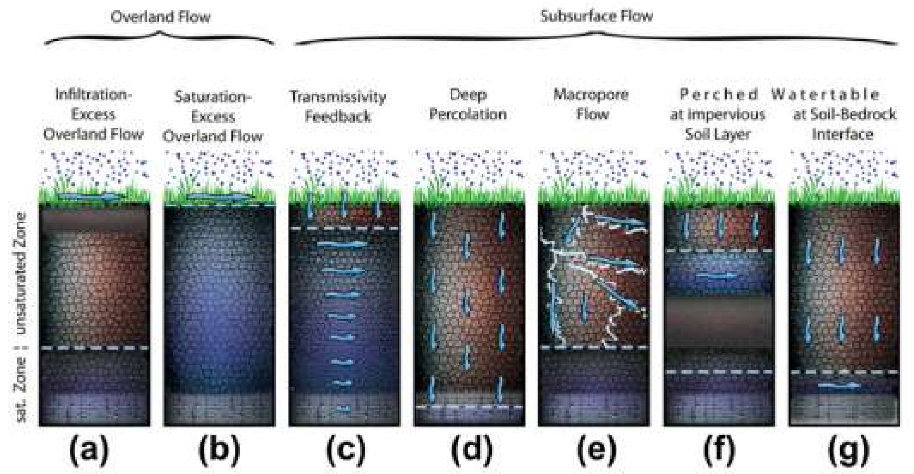


FIGURE 1 Different types of surface and subsurface runoff processes: If infiltration capacity (a) or storage capacity (b) of the soil layers at or near the surface is exceeded, overland flow is generated. As groundwater rises into more transmissive soil layers (c), lateral subsurface runoff increases. If the soil has a coarse texture and the bedrock is highly permeable, the groundwater table tends to be low and soil water can percolate deep down into the soil or bedrock (d). If distinct horizontal macropores exist, the flow rates toward the nearest stream channel can be high and subsurface runoff therefore responsive (e). If a water-restricting layer exists within the soil profile (f) or at the soil–bedrock interface (g), a perched water table might form from time to time and lateral subsurface flow can occur within the saturated soil layer. *(Color version online and in color plate)*

Figure A.17: From Rinderer and Seibert (2012), page 517.

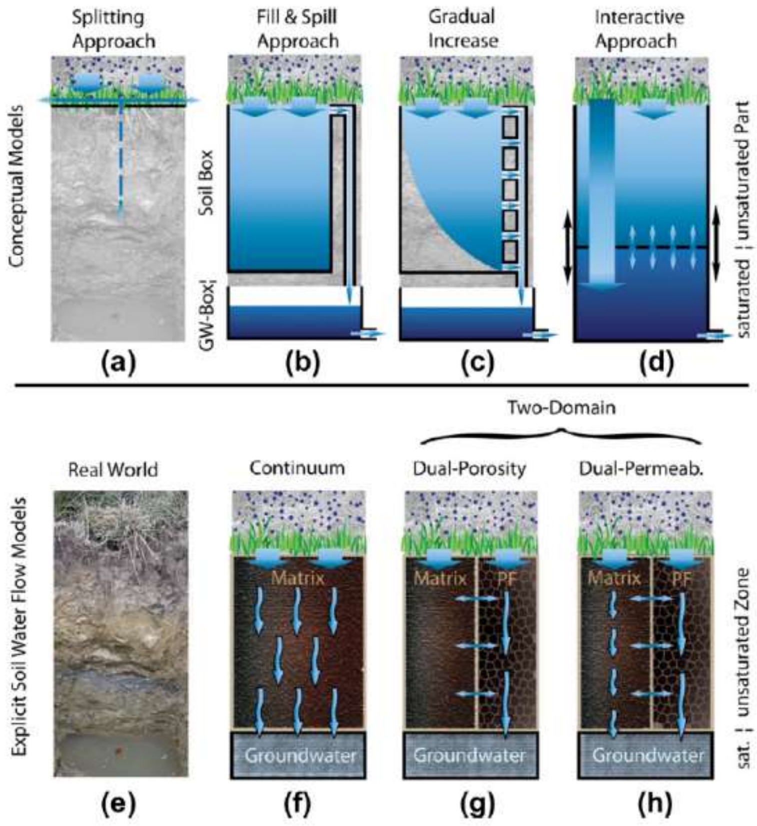


FIGURE 2 Conceptual and physically based modeling approaches of subsurface flow or soil storage response: Upper row shows conceptual modeling approaches of soil-water-storage outflow: (a) only accounting for surface runoff caused by infiltration excess; generating soil water outflow if bucket is (b) completely or (c) partly filled; and accounting for (d) interactions between saturated and unsaturated soil water storage. Lower row shows explicit soil water flow modeling approaches which can be categorized as (f) continuum approaches, which only account for matrix flow, and (g, h) two-domain approaches, which consider both matrix and preferential flow (PF). *(Color version online and in color plate)*

Figure A.18: From Rinderer and Seibert (2012), page 518.

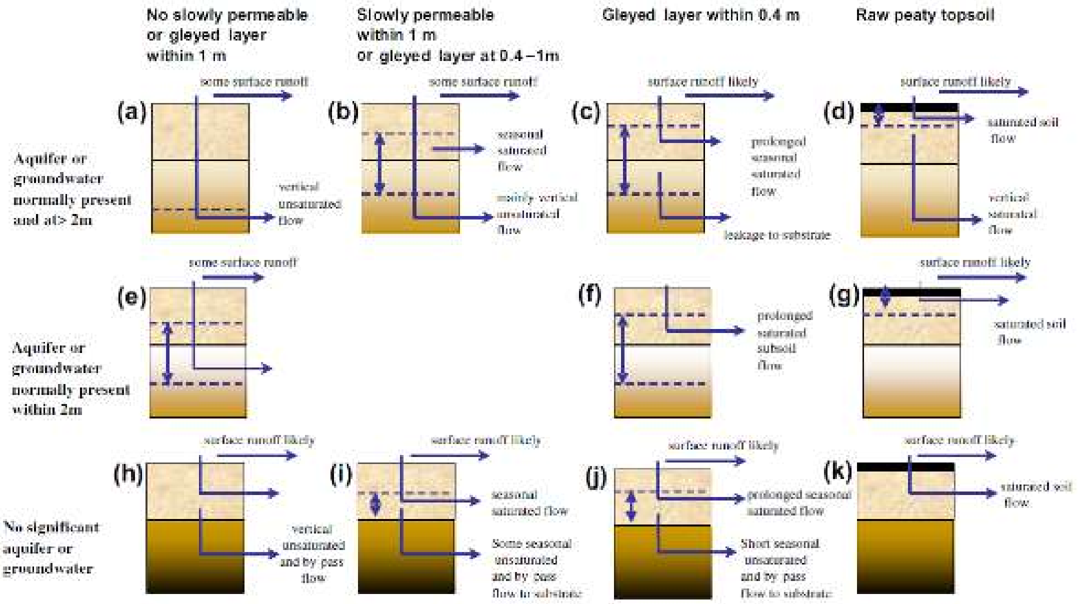


FIGURE 1 The Hydrology of Soil Types (HOST) classification of 11 conceptual models of flowpaths within the soil and substrate. *(From Boorman et al., 1995) (Color version online and in color plate)*

Figure A.19: Subsurface flow networks at the hillslope scale: detection and modelling (Lilly et al., 2012).

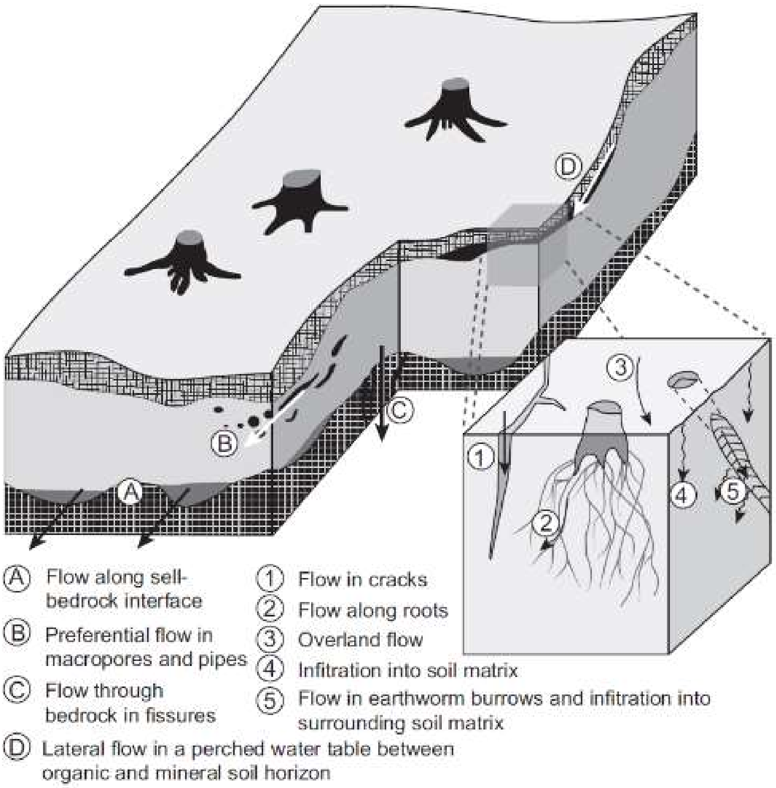


FIGURE 1 A conceptual model of subsurface preferential flow network (both vertical and lateral) in a forested hillslope, where lateral flow network consists of flow along the soil–bedrock interface, flow through macropores and along soil horizons, and flow through fractures in the underlying bedrock. *(From Sidle et al., 2001)*

Figure A.20: From Graham and Lin (2012).

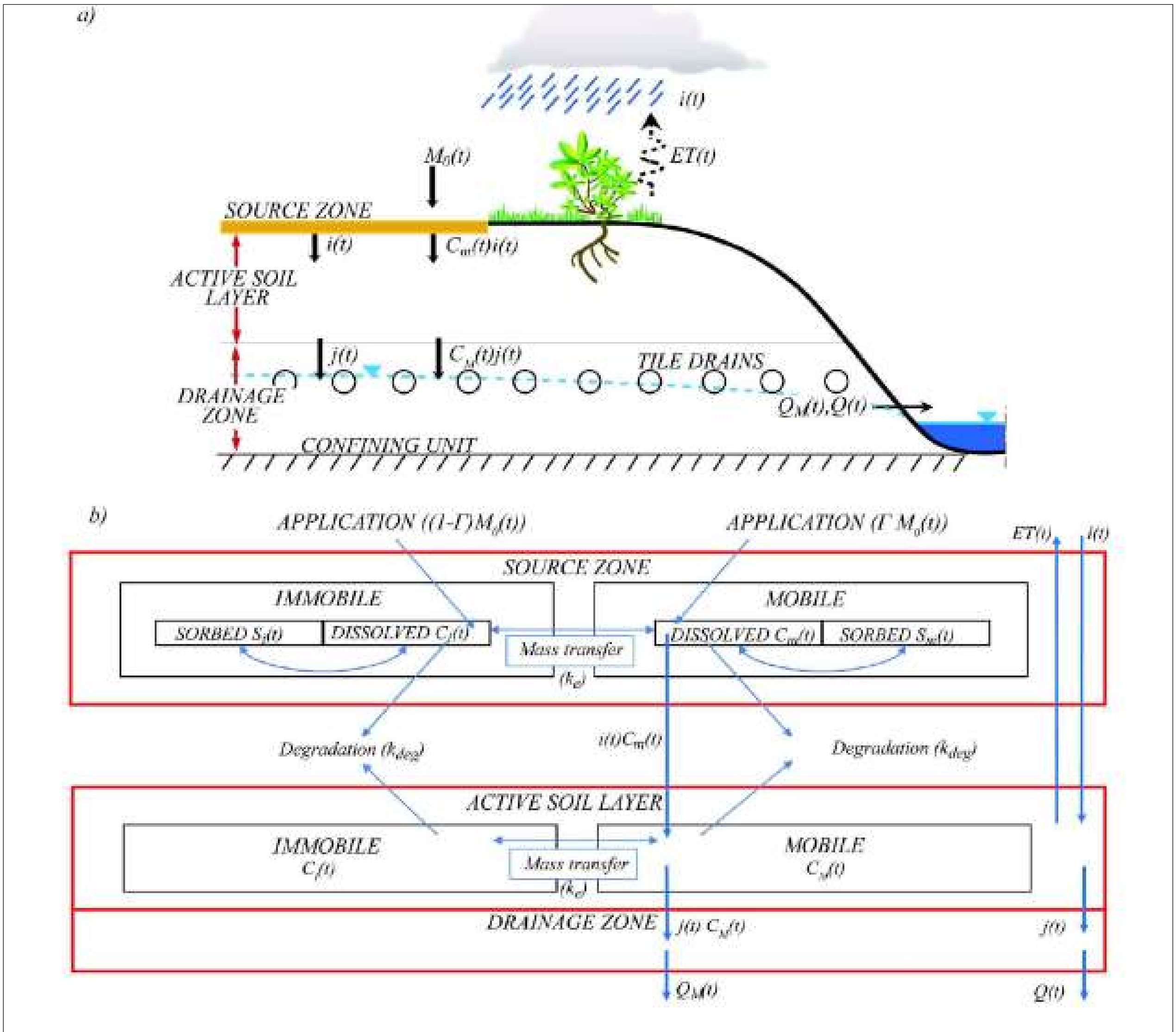
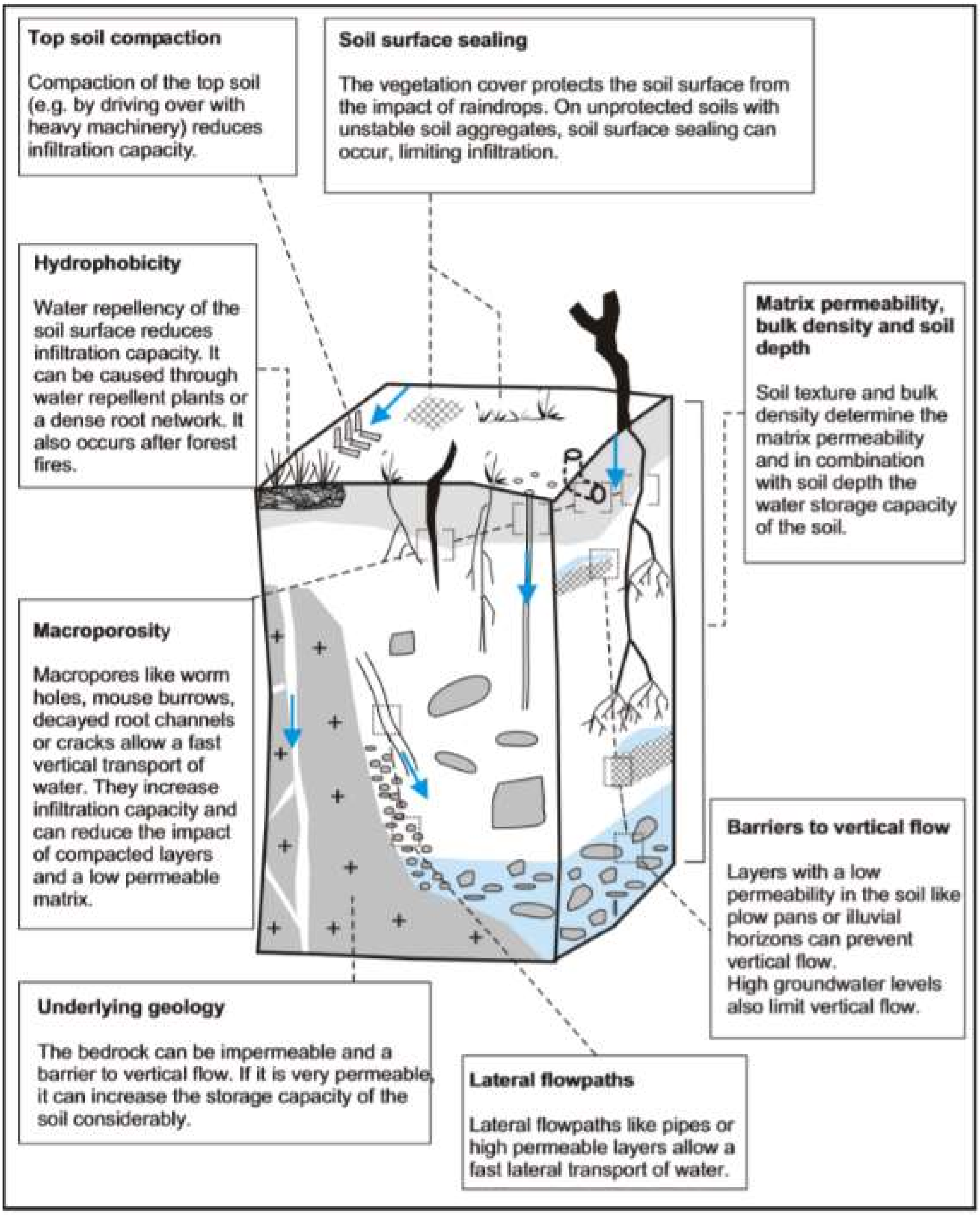


Figure 1. (a) Physical and (b) conceptual representation of the hydrologic and biogeochemical models.

Figure A.21: From Zanardo et al. (2012).



Top soil compaction

Compaction of the top soil (e.g. by driving over with heavy machinery) reduces infiltration capacity.

Soil surface sealing

The vegetation cover protects the soil surface from the impact of raindrops. On unprotected soils with unstable soil aggregates, soil surface sealing can occur, limiting infiltration.

Hydrophobicity

Water repellency of the soil surface reduces infiltration capacity. It can be caused through water repellent plants or a dense root network. It also occurs after forest fires.

Matrix permeability, bulk density and soil depth

Soil texture and bulk density determine the matrix permeability and in combination with soil depth the water storage capacity of the soil.

Macroporosity

Macropores like worm holes, mouse burrows, decayed root channels or cracks allow a fast vertical transport of water. They increase infiltration capacity and can reduce the impact of compacted layers and a low permeable matrix.

Barriers to vertical flow

Layers with a low permeability in the soil like plow pans or illuvial horizons can prevent vertical flow.
High groundwater levels also limit vertical flow.

Underlying geology

The bedrock can be impermeable and a barrier to vertical flow. If it is very permeable, it can increase the storage capacity of the soil considerably.

Lateral flowpaths

Lateral flowpaths like pipes or high permeable layers allow a fast lateral transport of water.

Fig. 4.1 Schematic representation of runoff formation on a soil profile (after Naef and Scherrer, 2003).

Figure A.22: From Schmocker-Fackel (2004).

Fig. 8 Classification tree for prediction of the risk of pollution of ground water by pesticides

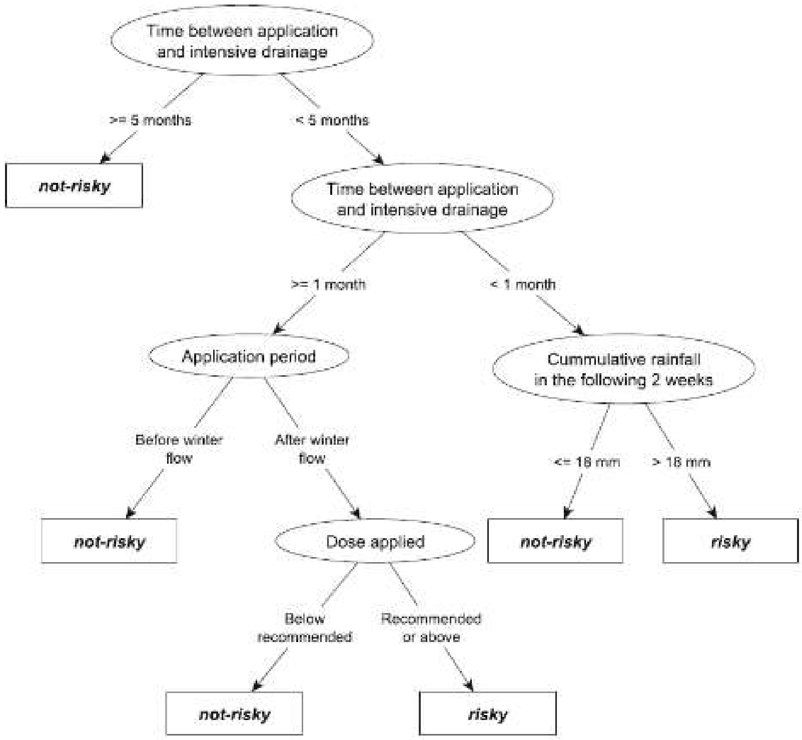


Figure A.23: From Trajanov et al. (2018).

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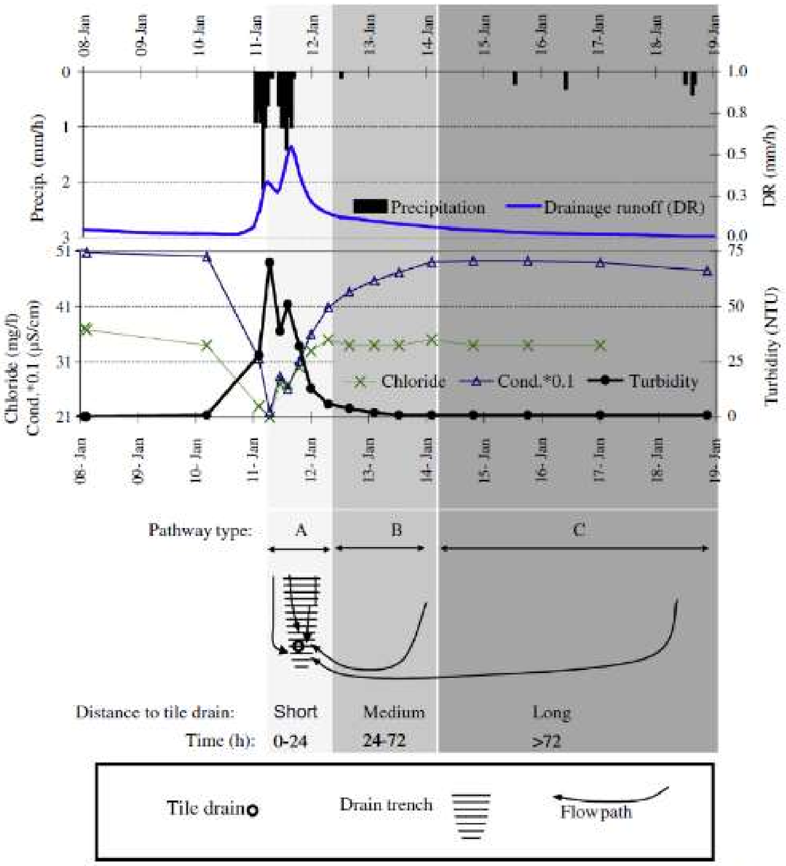

Fig. 6. Hourly precipitation and drainage runoff together with measured chloride concentration, conductivity and turbidity (lower graph). The shaded areas indicate the dominant transport pathways (types A–C) feeding into the sampled drainage water during the flow event. While "time" and "pathway types" are classified directly from measured data, "distance to tile drain" and shown water flow pathways are indicative providing our interpretation of measured data. (see Section 3.3)

Figure A.24: From Kjaer et al. (2011).

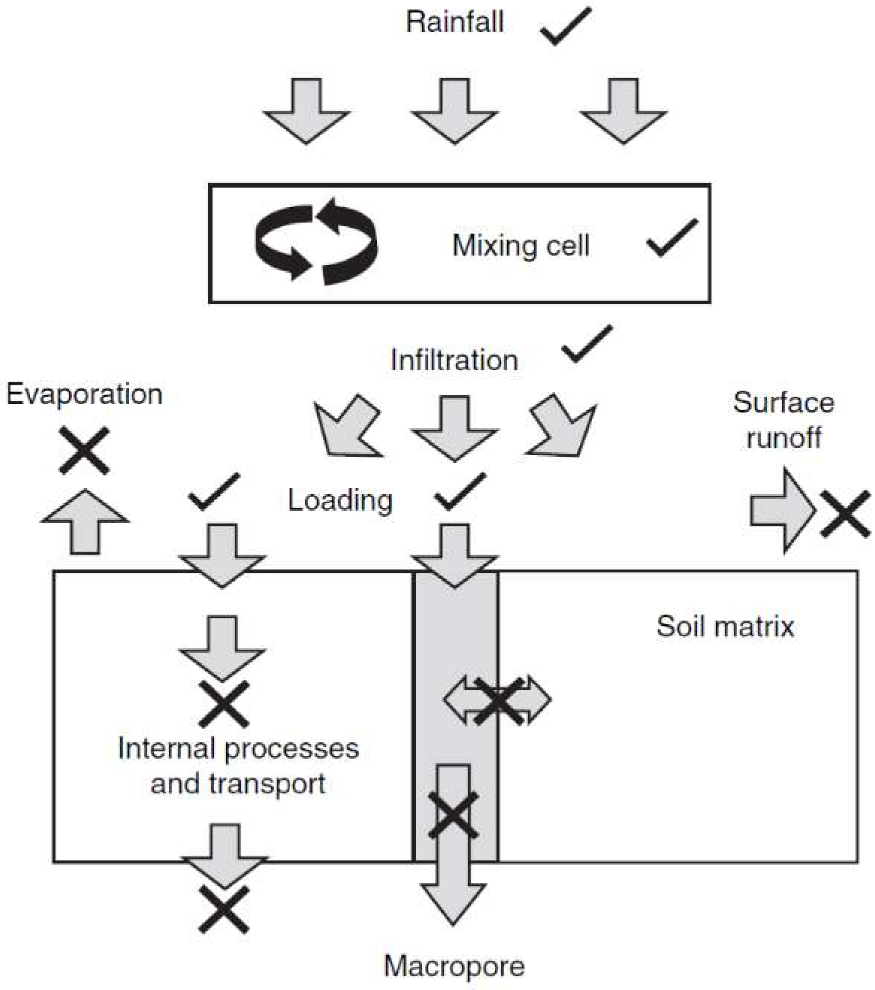

Figure 1 Conceptual model description, showing the mixing of solute by rainfall and the partitioning of water and solutes between the slow soil matrix and the fast macropore flow pathways. Highlighted also is what is not modelled, the solute transport in either of these pathways.

Figure A.25: From McGrath et al. (2008).

7.2 A.2. Conclusion from the FOOTPRINT report: "State of the art review on preferential flow" (Jarvis and Dubus, 2006)

"SUMMARY OF CURRENT UNDERSTANDING

It seems clear from the review of the literature presented in this paper that a great deal is known and understood about the effects of macropore flow on solute transport. Indeed, despite the complexity of the processes, a broad consensus seems to have emerged. The following ten major conclusions can be identified:

1.) *macropores are structural pores (root channels, earthworm channels, fissures and inter-aggregate packing voids) of large diameter, high continuity and low tortuosity that allow the maintenance of marked lateral physical non-equilibrium conditions during vertical flow and transport. From a pragmatic 'functional' point of view, pores larger than ca. 0.3 mm in diameter can be considered as macropores.*
2.) *Although the physical mechanisms of water flow in macropores are complex, it is clear that the assumptions underlying Darcy's law are not always met: macropore flow occurs predominantly under the influence of gravity (capillarity is negligible), inertial forces are certainly not negligible, and turbulent flow may even occur in large macropores at high input rates (e.g. under ponding).*
3.) *The physical, chemical and biological micro-environment in macropores contrasts strongly with the bulk soil. Organic and inorganic linings and coatings in biotic macropores and on aggregate surfaces restrict lateral mass transfer, enhancing non-equilibrium water flow and solute transport. Macropores are biological 'hot-spots' in soil, and may also have more chemically reactive surfaces. However, sorption retardation in macropores seems always less than in the bulk soil, partly due to the low ratio of surface area to pore volume, but also due to kinetic (chemical nonequilibrium) effects during transport.*
4.) *Soil macropore networks are hierarchical in nature. Larger macropores are generally more continuous, less tortuous and more widely spaced, which generates faster water flow, weaker lateral mass exchange, less sorption interaction and therefore stronger physical and chemical non-equilibrium.*
5.) *Surface boundary conditions exert a strong control on non-equilibrium water flow and solute transport. High intensity and long duration rain generates pressures closer to saturation that allow larger macropores to take part in the transport process, leading to the consequences listed under point 4.) above.*
6.) *The effects of initial conditions are complex, especially for soils that become water repellent when dry, or where the structure is a dynamic function of water content (i.e. swell/shrink clay soils). However, in the absence of such complications (which are not especially unusual), wetter soils will clearly generate more macropore flow.*
7.) *The strength of non-equilibrium water flow and solute transport is closely related to the observed morphology of soil horizons and pedons (e.g. size distribution of biotic macropores, grade of aggregate development and presence of aggregate skins). Basic soil properties (e.g. texture, organic matter content) also exert a strong control on macropore flow and transport, both through their effect on matrix hydraulic properties and also due to their strong influence on soil aggregation. The aggregate hierarchy is better developed in soils of smaller clay content and larger organic matter content, which are therefore less susceptible to non-equilibrium water flow and solute transport (see point 4. above).*
8.) *The impact of macropore flow on agrochemical leaching depends strongly on the solute properties controlling sorption and transformation processes, and on whether the chemical is indigenous to the soil or not. Although macropore flow will dramatically increase leaching losses of otherwise non-leachable substances that are foreign to the soil (e.g. strongly sorbing organic contaminants that are quickly degraded), it may actually decrease the leaching of indigenous mobile solutes like nitrate.*
9.) *Soil tillage and traffic strongly affect macropore flow and transport. Physical non-equilibrium is practically eliminated in the upper few centimeters of soil by intensive secondary cultivation performed to create a seedbed. Primary cultivation implements that invert and break up the soil disrupt the continuity of biopores (at least for some months), but non-equilibrium flow and transport can still take place along inter-aggregate packing voids. Macropore flow can also be generated by the abrupt change in matrix conductivity in compacted zones or 'pans' at the base of the plough layer. Compared to conventional tillage, many soils under no-till arable management (especially weakly aggregated ones) show a greater propensity for non-equilibrium solute transport, due to well-developed networks of earthworm channels. However, this may not always lead to increases in agrochemical leaching. For example, conventional tillage may result in greater losses if particle-bound transport in macropores is a dominant leaching mechanism.*

10.) *Land use and cropping influence soil structure and macropore flow. Non-equilibrium flow and transport seems generally weaker under long-term grassland than on arable land, presumably due to increased organic matter contents under grass, increased earthworm casting activity and root development, and less traffic compaction, all of which results in the preservation of a 'finer' soil structure and therefore slower flow and stronger lateral mass exchange."*