National Institute for Public Health
and the Environment
Ministry of Health, Welfare and Sport

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Soilless cultivations in greenhouses

RIVM Report 2015-0128

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Colophon

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Synopsis

Scenarios for exposure of aquatic organisms to plant protection products in the Netherlands.
Soilless cultivations in greenhouses

New methodologies for the assessment of the exposure of aquatic organisms to plant protection products (PPP) after their use in substrate cultivations in greenhouses were developed. The relevant protection goal is the aquatic ecosystem. In contrast with the current methodology, which was not specifically developed for substrate cultivations, the new methodology accounts for two major potential emission routes: the discharge of recirculation water and the discharge of filter cleaning water into surface water. The Dutch Ministry of Economic Affairs and the Ministry of Infrastructure and the Environment initiated this research to develop an exposure assessment methodology suitable for substrate cultivations in greenhouses.

The new methodology assigns substrate cultivations to four different crop groups according to their water requirement and sodium tolerance. For each of the groups an assessment scenario was developed, taking into account nutrient emission limits. A representative discharge-receiving ditch was selected and parameterised. For each scenario and PPP application method, the Greenhouse Emission Model calculates water flows and PPP behaviour in the growing system, emissions of water and PPP to surface water and the fate of the PPP in the surface water. The resulting concentrations in surface water can be used to decide on the authorisation of PPPs.

Keywords: plant protection products, authorisation, covered crops, emission, exposure, environmental risk assessment, surface water

Publiekssamenvatting

Scenario's voor de berekening van de blootstelling van waterorganismen aan gewasbeschermingsmiddelen.
Substraatteelt in kassen.

Als door het gebruik van gewasbeschermingsmiddelen in kassen restanten van deze middelen in het nabijgelegen oppervlaktewater terechtkomen, kan dat het waterleven aantasten. Hiermee wordt te weinig rekening gehouden bij de huidige risicobeoordeling van het gebruik van een gewasbeschermingsmiddel voor gewassen die in kassen op substraat, bijvoorbeeld steenwol, worden geteeld. Daarom zijn voor deze toepassingen nieuwe methoden voor de risicobeoordeling ontwikkeld waarin dat wel is ingecalculeerd.

Bij de meeste substraatteelten wordt water zoveel mogelijk opnieuw gebruikt. Gedurende dit proces neemt de concentratie van zouten en andere stoffen toe, waardoor zo nu en dan 'vervuild' water moet worden geloosd en vers water moet worden toegevoegd. Ook moeten filters worden schoongespoeld.

De nieuwe methoden omvatten scenario's voor vier groepen gewassen (vertegenwoordigd door roos, ficus, tomaat en paprika) waarmee de lozingen en resulterende concentraties in oppervlaktewater door het jaar heen kunnen worden berekend. De indeling in de gewasgroepen is gemaakt op basis van de mate waarin gewassen behoefte aan water hebben en zout verdragen. De mate waarin restanten van gewasbeschermingsmiddelen in het oppervlaktewater komen is onder andere afhankelijk van het teeltsysteem, de wijze van toediening van het gewasbeschermingsmiddel, de mate waarin planten het middel opnemen en de snelheid waarmee het middel in water wordt afgebroken.

De methoden zijn ontwikkeld door het RIVM, de onderzoeksinstituten Alterra en Wageningen UR Glastuinbouw en het College voor de toelating van gewasbeschermingsmiddelen en biociden (Ctgb).

Kernwoorden: gewasbeschermingsmiddelen, bedekte teelt, emissie, oppervlaktewater, milieu, risico evaluatie, toelatingsbeoordeling

Contents

Summary

During the last few decades, more and more crop-growing systems have changed from soil-bound to soilless cultivation in often high-tech greenhouses. The environmental risk assessment methodology for applications of plant protection products (PPP) to crops in greenhouses has not been updated since the early 1980s and does not account for major potential emission routes such as the discharge of deteriorated recirculation water and discharges from the cleaning of filters. This report describes methodology that can be used to perform surface water exposure assessments as part of an overall environmental risk assessment for such systems. The relevant protection goal is the aquatic ecosystem in discharge-receiving ditches. The methodology is intended to cover all soilless greenhouse crops in the Netherlands and the most common irrigation and PPP application techniques.

The proposed methodology uses three models to calculate the environmental fate and behaviour of PPP in soilless growing systems and in surface water after discharge. The WATERSTREAMS model is used to calculate water flows in the greenhouse, based on climatic conditions outside the greenhouse, crop characteristics such as water requirement and sodium tolerance, crop management decisions and quality of available water sources. A substance fate model is used to calculate the degradation, plant uptake and distribution of PPPs in the system, including the concentration in water that is discharged to surface water. Finally, the TOXSWA model is used to calculate concentrations in surface water and sediment, including the endpoints (i.e. peak concentration and time-weighted average concentration), which can be used in risk assessments. The operation of the models is through a graphical user interface, while PPP parameters are stored in a separate database that is also used by other risk assessment tools.

In risk assessment, realistic worst case scenarios are usually used for the calculations. Ideally, the realistic worst case scenario is selected from a probability distribution of relevant scenarios. Unfortunately, however, the information necessary to establish the probability distribution for greenhouse growing systems is lacking. For example, there is no comprehensive data on the water sources used. Therefore, a more pragmatic approach was followed.

Crops grown on substrate in greenhouses were divided into four categories, based on their water requirement, sodium tolerance and growing system. For each category, a water supply and refreshment scenario was established using expert knowledge, taking account of nutrient emission limits set by the Dutch government for the various crops.

The discharge-receiving ditch was selected from a typical greenhouse area for which the hydrological situation is well understood and all necessary information on daily water flow velocities is available.

1 Introduction

1.1 Background

Soilless growing systems are common in greenhouse horticulture in most European countries, although they are not widely used in every country. Greenhouse horticulture has advantages over open field cultivation because the greenhouse protects the crop against adverse environmental conditions (EFSA 2010a, Stanghellini 2009, van der Linden 2009).

The total greenhouse area in the Netherlands is ca. 10,500 ha, of which 6,500 ha consist of soilless systems (Vermeulen PCM 2010). During the last ten years the total area of protected cultivation in the Netherlands has been rather stable, as has the area devoted to vegetables, flowers and pot plants. All fruit vegetables (tomato, cucumber, sweet pepper, eggplant) have changed from soil-bound to soilless cultivation (3,000 ha). The other (leaf) vegetable crops (including radish and lettuce; combined area approximately 1,000 ha) are still soil-bound. Some flower crops (rose, gerbera, anthurium, orchid; together 1,500 ha) and pot plants (2,000 ha) are grown in soilless systems.

The advantages of soilless systems over soil-bound systems are:

- Growth and yield are independent of the soil type of the cultivated area.
- Growth can be better controlled, for example by the use of high-quality water and more efficient fertigation.
- Products are of higher quality, partly as a result of better growth control.
- A pathogen-free start to the cultivation can be achieved more easily as well as the control of root pathogens.

There are disadvantages as well:

- There is a need for high water quality, i.e. water with low content of substances detrimental or not beneficial to the plants, amongst others because of the risk of dispersal in the system.
- It is expensive to install and maintain the necessary equipment (e.g. fertigation unit, disinfection equipment and filtering systems for recirculation).
- The costs of fertilising are relatively high, because fertilisers of high quality are required in order to ensure good growth conditions.

Often the advantages outweigh the disadvantages. The disadvantage of the potential dispersal of pathogens is overcome by disinfecting the recirculating solution, mostly with heat treatment or UV radiation treatment, while the accumulation of coarse-grained organic substances is controlled by filtration.

Several forms of soilless cultivation exist. In the context of this report, a distinction is made between cultivations without recirculation of the nutrient solution, also referred to as ‘open’ or ‘run-to-waste’ systems, and recirculation systems, also referred to as 'closed systems' or 'closed loop systems'. Whereas outside the Netherlands non-recirculating systems are predominant, in the Netherlands, in most cases, recirculating systems are compulsory[1]. In comparison, recirculating systems are more efficient with respect to the use of water and nutrients, and lower emissions of substances to the environment are expected. Significant potential disadvantages of recirculating systems are the risk of rapid dispersal of (root) pathogens and phytotoxic substances with the recirculating solution and the accumulation of salt and organic substances in the system.

As stated above, recirculating systems are predominant in the Netherlands. Dutch legislation (Besluit Glastuinbouw, LNV 2002) prescribes the use of recirculating systems in soilless cultivations[1], with discharge permitted only when sodium concentrations in the recirculating solution exceed crop-specific threshold levels (see Appendix B). It is also compulsory to collect rainwater[2] and condensation water and use these as the preferred water sources. In practice, these sources are often mixed or used both at the same time to meet the water demand of the crop. Figure 1-1 gives a schematic overview of the water fluxes in a soilless growing system.

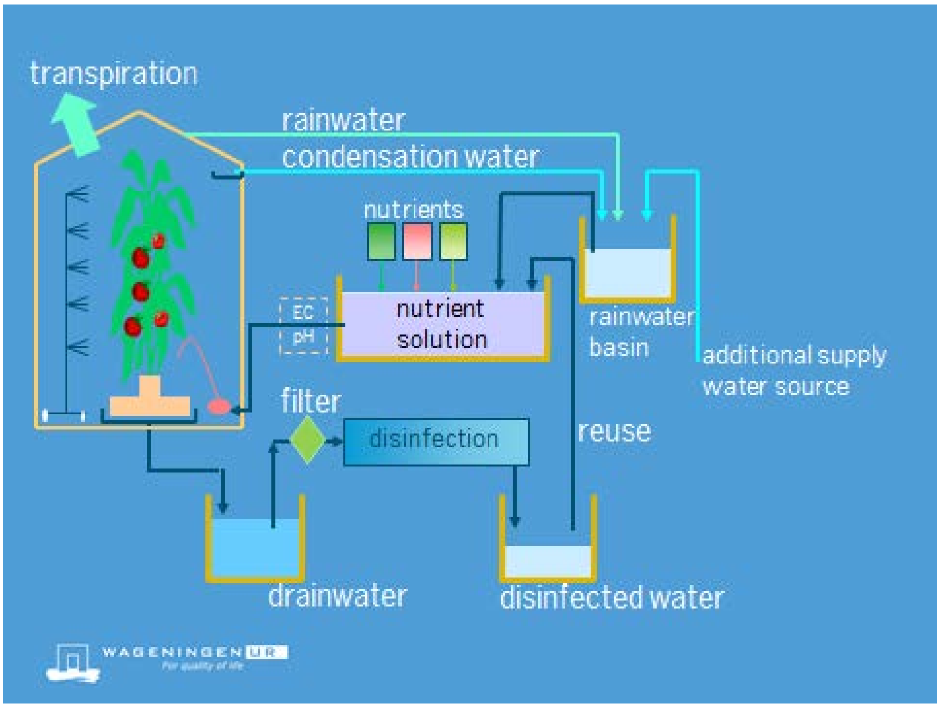

Figure 1-1 Schematised water flows in a greenhouse with a soilless recirculation system. The flows Condensation water and Additional supply may, dependent on local conditions, be directed to the disinfected water reservoir or a supplementary water storage tank (not shown in the figure).

[1] There are some exceptions, such as an exemption for small enterprises and for crops for which recirculation systems are inadequate (Activiteitenbesluit Milieubeheer (Anonymous. 2012. Activiteiten Besluit Milieubeheer. Besluit van 14 september 2012 tot wijziging van het Besluit algemene regels voor inrichtingen milieubeheer.).
[2] With some exceptions; see footnote 1.

Although the use of recirculating systems is compulsory in soilless cultivations, the presence of plant protection products (PPPs) in surface water above water quality standards in greenhouse areas suggests that emissions to surface water are underestimated in the current authorisation process.

In the earlier phases of this project the general characteristics of soilless cultivation in the Netherlands were identified, in terms of both the layout of the systems and management practices (Cuijpers et al. 2008, Vermeulen T. et al. 2010), and it was concluded that major potential emission routes are not included in the current risk assessment. This report describes a new methodology that takes into account the major emission routes – discharges of deteriorated nutrient solution and filter rinsing water – and predicts the resulting concentrations in surface water.

Recently, the legal basis for discharging deteriorated nutrient solution has changed to limits on the total discharge of nutrients (Activiteitenbesluit Milieubeheer, Anonymous 2012). In order to adhere to this new legal basis, the working group developed water and nutrient management scenarios while retaining the sodium content of the nutrient solution as the major driving force for discharging deteriorated nutrient solution. The scenarios comply with the nutrient emission limits while respecting the sodium tolerance of the respective crops.

1.2 Remit

The risk assessment methodology for the use of PPPs in greenhouses regarding their potential environmental impact has not changed for the last 30 years. As reported earlier (Cuijpers et al. 2008, Vermeulen T. et al. 2010), the current methods do not reflect agricultural practices in soilless cultivations as they do not account for potential major emission routes to surface water. The Dutch government considered this situation no longer defensible and therefore formed a working group to develop risk assessment methodology for soilless growing systems. The methodology was to (1) reflect current agricultural practice in greenhouse horticulture, (2) be in line with the latest knowledge and (3) be easy to incorporate into the authorisation procedure.

The working group on soilless covered crops adopted the following principles for establishing the methodology and scenarios:

- The scenarios and methodology should be developed in close collaboration with the Dutch working group on soil-bound greenhouse cultivation, especially with regard to the selection of the receiving watercourse.
- The working group should adopt the approaches of the Dutch working group ‘Exposure of Water Organisms’ when applicable.
- The developed scenarios should not conflict with EU regulation 1107/2009 (EU 2009).
- The working group should have regular contact with the Dutch Board for the Authorisation of Plant Protection Products and Biocides (Ctgb).

1.3 Structure of report and reading guidance

This report describes the specific methodology that has been developed for performing exposure assessments of PPPs in surface water after use in soilless cultivation in greenhouses in the Netherlands. It also explains the derivation of the scenarios. A similar methodology for soil-bound cultivations in greenhouses is described in Wipfler et al. (2015a).

Ideally, the derivation of such scenarios is based on (1) a priori knowledge of growing systems and their management, (2) the characteristics of environmental receptors and (3) broadly accepted, validated models for calculating emissions and resulting concentrations in the environmental receptor in question (see, for example, EFSA 2012a and EFSA 2012b). Appropriate scenarios are then derived by calculating emissions for a large number of situations and substances and selecting relevant ones, taking into account the specific protection goals for the environmental receptors. As basic knowledge of the growing systems and the characteristics of water bodies in greenhouse areas was largely missing, a more pragmatic approach was followed in this study.

Chapter 2 of this report outlines the risk management decisions underlying the procedure and the interpretation of these decisions by the working group. Chapter 3 describes the selection of greenhouse systems and the grouping of the crops grown on soilless systems, as well as water management and agricultural practice in the systems. These practices determine the need to discharge deteriorated nutrient solution and, potentially, PPPs to surface water. Chapter 4 explains the selection and the parameterisation of the ditch into which the deteriorated nutrient solution is considered to be discharged. The results of the procedures described in Chapters 3 and 4 are input into the models for calculating water flows and substance behaviour in substrate cultivations and, after discharge, in surface water. These models are presented in Chapter 5. The models and scenarios are implemented in the software package GEM (Greenhouse Emission Model). An outline of this package is given in Chapter 6, together with a description of the use of the system and some sample results. Finally, Chapter 7 gives conclusions and recommendations.

2 Risk management decisions

2.1 Risk managers' decisions

The purpose of this report is to establish a specific risk assessment methodology for the exposure of aquatic organisms to plant protection products (PPPs) after their use on substrate (soilless) cultivations in greenhouses in the Netherlands, including the scenarios for which the assessments are performed. The methodology will then be implemented in the authorisation process in the Netherlands in the form of an easy-to-use software package.

In this report, it is understood that risk managers are those at the Ministry of Economic Affairs and the Ministry of Infrastructure and the Environment who are responsible for preparing and implementing legislation with regard to the authorisation of PPPs in the Netherlands. These persons took all risk management decisions that are implemented and will decide later on some open issues, e.g. which concentration (the 50th or the 90th percentile) in surface water to use in the assessment.

The foundation of a robust and efficient environmental risk assessment procedure is a clear specific protection goal. Risk assessors need to know what the risk managers want to protect, where to protect it and over what period (EFSA 2010b). Based on knowledge gained in earlier phases of the project (Cuijpers et al. 2008, Vermeulen T. et al. 2010), the risk managers agreed to base the scenario development on the following principles and boundary conditions:

1) To use a small number of scenarios, covering high and low salt (sodium) tolerance and high and low water requirement.
2) That the population of watercourses should comprise all edge-of-field watercourses. Larger water bodies such as ponds, lakes and rivers should not be included in the population, because they are usually not edge-of–field watercourses.
3) To use a central value of the exposure concentrations in the risk assessment, i.e. a concentration closer to the 50th percentile and not the realistic worst case (90th percentile), which is normally used.
4) Not to take PPP removal processes in sewage treatment plants into account.
5) To include a simple option for water treatment in the software package, i.e. the software package should be able to indicate the effect of treatment of water before discharge on the calculated PPP concentrations in the watercourse.

A consideration with respect to the third point is that developments in the area of covered crop production and environmental risk assessment are rapid. Setting strict criteria at this time might unnecessarily restrict further technical and business development and progress in environmental risk assessment.

2.2 Interpretation of management decisions by the working group

The boundary condition of a limited number of scenarios requires the categorisation of crops and growing systems. To cover both low and high salt tolerance as well as low and high water requirement, at least four scenarios are required.

In open field risk assessment, the translation of the specific protection goal to scenario selection is usually to take a situation that ranks approximately at the 90th percentile. EFSA (2012a) gives a number of aspects that should be taken into account when selecting scenarios:

1) The basic unit and the population of these units (usually a cropping system covering 1 ha).
2) Temporal aspects, i.e. variability in exposure concentrations over time (for example the variability in weather conditions in a particular location).
3) Spatial aspects, i.e. variability in exposure concentrations due to location-dependent properties (for example, available water sources and size and management of discharge-receiving ditches).
4) Substance properties; variability in substance properties may independently or in combination with temporal and spatial aspects lead to different exposure concentrations.

With regard to soilless cultivation in the Netherlands, information about spatial aspects is rather poor. For instance, there are no comprehensive or representative databases on water sources used, discharge strategies or crop management. Therefore, a fully quantitative approach to scenario selection is impossible. Furthermore, a general policy to reduce emissions of nutrients stepwise has been put forward (Anonymous 2012). Implementation of the general policy causes available information to be outdated rather quickly.

Instead of a fully quantitative approach, a more pragmatic approach was followed. It was decided to categorise crops on the basis of their water demand, dominant growing system and salt tolerance, and to construct, based on expert knowledge of the specific growing systems and taking into account the nutrient emission limits, in-greenhouse scenarios for each category. The aim was to develop scenarios representing realistic worst case situations for each category. Scenarios are based on discharges into a representative ditch, selected from ditches in one of the larger greenhouse areas in the Netherlands. In the selection, ditch types were weighted according to their occurrence in greenhouse areas. Concentrations of a particular substance in the surface water are then derived by model calculations over an appropriate time series. Specific aspects of the scenarios are given in detail in the following chapters.

As the risk managers have not yet decided on the concentration percentile to be used in the risk assessment, this percentile can be set at the start of the calculation procedure to either the 50th or the 90th percentile. The software uses those input values to select the appropriate output from the calculation results.

2.2.1 *Endpoint of the exposure assessment*

The working group on aquatic effects identified multiple Ecologically Relevant Concentrations (ERC, see Brock et al. 2011). They proposed that the endpoint of the exposure assessment should be either the annual peak concentration or the annual maximum Time Weighted Average (TWA) within one calendar year or part of a calendar year. These two endpoints may lead to different scenarios. Following the working group that developed scenarios for field crops (Tiktak et al. 2012), the working group decided to use the annual peak concentration in water for the water body selection. The scenarios do not take into account the exposure of organisms in sediment. The working group further decided that the assumed endpoint of the exposure assessment should be 100 m of ditch downstream of the greenhouse discharge point (Figure 2-1). The peak concentration is considered to be the maximum average hourly concentration over these 100 m of ditch.

Several systems for purifying water discharged from greenhouses have been studied recently (van Ruijven et al. 2013) and high removal rates have been obtained during the first trials (on average 80% of PPPs were removed). As it is unclear which of the various systems is most likely to be introduced, it was decided to include a purification factor in the model. This factor can be used to calculate the effect of a specific removal rate on the concentrations in surface water. The use of this purification factor in the authorisation procedure is still under discussion at risk manager level. It is envisaged that this factor will be used to estimate the minimum purification required. Removal rates are not taken into account in the scenario selection procedure.

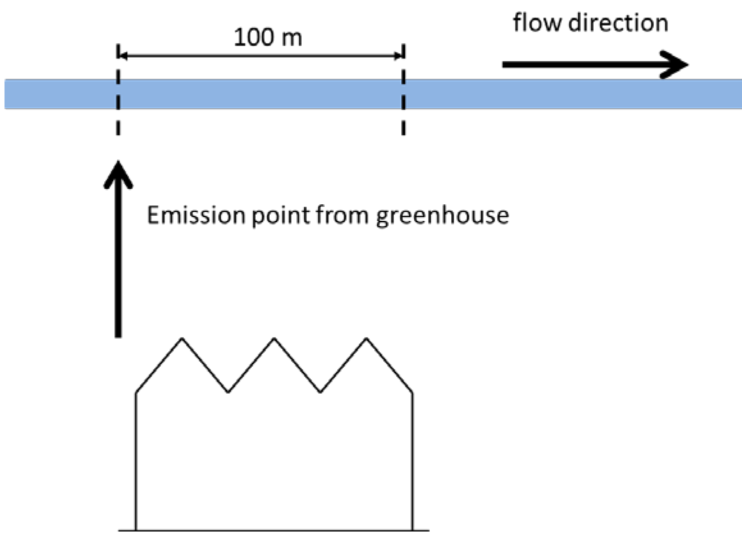

Figure 2-1 The endpoint of the exposure assessment for PPP used on greenhouse horticulture crops is defined as the annual peak concentration and the TWA over a 100 m length of ditch downstream of the greenhouse discharge point. The discharge is considered to be a point emission.

3 Crops, cropping systems and crop scenario development

In the earlier phase of the working group's study, sodium concentration in the recirculating nutrient solution was identified as a quantifiable determinant of emissions to surface water (Besluit Glastuinbouw, LNV 2002). Recently, however, the focus of growers' management has moved to emissions of nutrients (mainly N) to surface water as limits on emissions of these have been set in regulations (Activiteitenbesluit Milieubeheer, Anonymous 2012; Water Framework Directive, EU 2000). In consultation with the relevant risk managers at the ministries, the working group considered it appropriate to develop scenarios that are in line with current growers' management strategies and regulations.

Growers discharge nutrient solution for three reasons: (1) to control sodium concentration, (2) as part of the filter rinsing process and (3) to (arbitrarily) refresh the solution. In order to stay within the limits for nutrient emissions, they have to develop specific water and nutrient management strategies. Expert judgement was applied to quantify both current and likely future strategies. The resulting emission scenarios are described in this chapter.

3.1 Crops in soilless systems

The total greenhouse area in The Netherlands (10,000 ha) is divided between soilless (6,500 ha) and soil-bound (3,500 ha) crops. For most crops grown in greenhouses in the Netherlands, either soilless or soil-bound cultivation is dominant. Here soilless means predominantly growing in all kinds of substrates (e.g. stone wool, coir, peat, perlite), with <5% growing in a nutrient solution without a substrate. From the quantitative information on greenhouse horticulture from 2012 (Vermeulen PCM 2012), the area of soilless crops can be divided as shown in Table 3-1.

Table 3-1 Area of soilless cultivation per group of crops (Vermeulen PCM 2012).

Group	Area (ha)	Crops
pot plants	2,000	all
vegetables	3,000	tomato, sweet pepper, cucumber, strawberry, aubergine
floriculture	1,500	rose, gerbera, anthurium

In the Netherlands, little diversity is found at the level of growing systems. The predominant growing systems for specific crops are shown in Table 3-2.

Table 3-2 Cultivation and irrigation system per crop.

Crop	**Growing system**	**Irrigation system**
fruit/vegetables	substrate – stone wool or coir	drip irrigation
roses, gerbera	substrate – stone wool or coir	drip irrigation
anthurium, cymbidium (cut flower)	substrate – perlite, lava	drip irrigation
strawberry, small fruit	substrate – peat	drip irrigation
pot plants	substrate – peat, clay or lava granulates	ebb/flow
starting material (fruit vegetables, roses)	substrate – stone wool or coir	ebb/flow
phalaenopsis	substrate – bark	overhead irrigation
lettuce, radish, other cut flowers, herbs	soil-bound	overhead irrigation

The distinction between drip irrigation, ebb/flow and overhead irrigation is most important for emission flows and registration of PPPs (Vermeulen T. et al. 2010). The working group developed scenarios for drip irrigation and ebb/flow irrigation, these being the most frequently used irrigation techniques.

3.2 Nitrogen emission

During the last five to ten years it has become clear that the limits on the use nitrogen in soilless cultivation given in the regulation Gebruiksnormen, Besluit Glastuinbouw (LNV 2002) are not useful in practice as they are not a good indicator of the level of emission of nitrogen to surface water. Therefore, a working group on emission policy (WG Glami) proposed limits on nitrogen emissions from greenhouses with soilless cultivation in the Netherlands. These emission limits have now replaced the use limits of the earlier regulation. Table 3-3 gives the nitrogen emission limits for various soilless crops and their changes over time. The limits for emissions will be reduced further to approach zero emission in 2027, in line with the EU Water Framework Directive (Table 3 in Anonymous 2012).

Table 3-3 Allowed discharge amounts of nitrogen (kg/ha/yr) per crop to achieve almost zero discharge by 2027 (Anonymous 2012).

Category	2012–2014	2015–2017	After 2017	Crops
1	25	25	25	other vegetables
2	50	33	25	anthurium, bedding plants
3	75	50	38	orchids (cymbidium)
4	100	67	50	tulip, annuals
5	125	83	67	tomato, herbs
6	150	100	75	cucumber, potting plants, starting material floriculture, other flower crops
7	200	133	100	strawberry, aubergine, sweet pepper
8	250	167	125	rose, gerbera, starting material vegetable crops
9	300	200	150	phalaenopsis, other potted orchids

3.3 Derivation of emission scenarios for PPPs

The discharge of water containing PPPs is the main source of PPPs in watercourses near soilless cultivation. Vermeulen T. et al. (2010) identified a number of water emission/discharge flows from soilless growing systems. Typical volumes (in descending order of (average) discharge volume) are:

	Discharge flow	Volume (m^3/ha/year)
1	recirculation water, based on Na	500–1,000
2	recirculation water, refreshing	500–1,000
3	condensation water – if not re-used	c. 1,000
4	filter rinsing water	250–500
5	leakage – 1.5% of water supply	c. 150
6	end-of-season discharge (vegetables)	60–80
7	accidents	c. 40
8	wash-off from end-of-season clean-up	c. 10
9	overspill from rain water basin (after first flush)	no information

The reuse of condensation water is compulsory in the Netherlands, making direct emission to surface water due to flow 3 irrelevant. Condensation water may contain amounts of sprayed PPPs, which enter the system upon reuse and are consequently subject to discharge via other emission routes. Leakage to soil is assumed to result in negligible emission to surface water. Overspill from rainwater basins may lead to the contamination of surface water when collected water contains PPPs (collection of the first flush is compulsory and condensation is sometimes collected in the rainwater basin). Vermeulen T. et al. (2010) assumed that condensation is collected in the fresh water tank and therefore does not lead to contamination of the water in the rainwater basin. Other contaminations of the rainwater basin are unlikely to be related to the growing system in the greenhouse and are therefore not considered in the assessment procedure for authorisation.

The main emission routes are therefore discharge flows 1, 2 and 4, i.e. the discharge of recirculation water and filter water. Discharge volumes may vary according to crop water need, crop sodium tolerance and crop management conditions. In the exposure assessment, these are considered the major determinants of emissions.

The formulation of realistic scenarios requires information on growing systems and their management (Section 3.3.1). This information is then used to derive the scenarios (Section 3.3.2).

3.3.1 *Overview of regional growing systems and management*

Within the Netherlands, an opinion survey was carried out among experts (approximately 20) from research institutes, technical installation companies, water boards and crop consultancies. On the basis of this survey, the following overview of horticultural regions with their typical water supply systems was constructed (Table 3-4).

Table 3-4 Description of typical greenhouse and cultivation characteristics in the different horticultural regions of the Netherlands.

	1	2	3	4	5	6	7
Region:	Aalsmeer	Westland ZH-islands N-Holland Oostland	Westland Oostland Aalsmeer	Flevoland C-rivers	Coast	Friesland East-NL Groningen Oostland	Brabant Limburg C-rivers
Area (ha):	1,000	1,500	1,000	500	500	500	1,500
Rainwater basin (m^3/ha)	500	1,500	2,500	3,000	1,500	4,000	1,000
[Na] (mmol/l) in:							
rainwater	0.1	0.1	0.1	0.1	0.5	0.1	0.1
reverse osmosis	0.1	0.1	0.1	--	0.1	--	--
well water	0.3	--	--	--	--	--	0.3
tap water	--	1.5	1.5	1.5	1.5	--	--
surface water	--	--	--	--	--	1.5	--
discharge water	(m^3/ha/yr)						
tomato	135	135	135	139	135	135	135
rose	145	146	171	268	740	161	163
ficus	79	79	79	79	113	79	79
discharge N	(kg/ha/yr)						
tomato	57	57	57	57	57	57	57
rose	33	33	39	61	168	36	37
ficus	17	17	17	17	17	17	17

The size of the rainwater collection basin and the sodium content in the (additional) water sources were found to affect the level of discharges and emissions to nearby watercourses (Vermeulen T. et al. 2010). Table 3-4 shows that the size of rainwater basins differs per region. Land prices and available space determine growers' choices, as does the availability of other high-quality water sources. For example, in Brabant and Limburg there is extensive use of well water (groundwater of good quality), which obviates the need to build large rainwater basins. It also appears that the use of reverse osmosis (RO) water is common in most regions. In general, groundwater is used in the preparation of RO water and the produced quantities of RO water are often enough to compensate for up to four weeks without rain.

The lower part of Table 3-4 gives estimates of the amounts of discharge water (m^3/ha/yr) and the amounts of nitrogen (kg/ha/yr) contained in it. Values are calculated using the WATERSTREAMS model (Voogt et al. 2012) for typical greenhouse layouts. The calculations assume typical nutrient supply and sodium tolerances of the various crops and emission strategies respecting the target limit values for the period 2015-2017. It appears that discharges do not vary much per region. Exceptional discharges were found only in the North Sea coast region (region 5). This is due to the higher sodium content in the rainwater in this region. Based on these figures, the working group decided not to distinguish between regions in this respect.

The differences between crops in terms of water discharge volumes and nitrogen emissions are larger than the differences between regions. Differences depend on the tolerance for and uptake of sodium of the crop.

On behalf of the LTO growers' association, van Paassen and Welles (2010) organised a survey among growers (10–30 growers for each crop) to obtain insights into water discharge and nitrogen emission values under current conditions. They found average discharge volumes for tomato, rose and ficus of 335, 1,358 and 484 m^3/ha/yr, respectively. The nitrogen emissions were respectively 110, 219 and 59 kg/ha/yr. Both the discharge volumes and the nitrogen emissions are higher than those calculated and presented in Table 3-4. On the one hand, this can be explained by the values in the table being target values whereas the values reported by van Paassen and Welles 2010 result from practice. On the other hand, it appears that management strategies also play an important role in the emission flows from soilless cultivation. It is expected that management decisions will become more important in practice as growers try to meet the future nitrogen emission limits.

3.3.2 Crop categories

The aim of the scenario development was to derive scenarios that are protective/conservative for the situations they represent. This means that emissions and the resulting concentrations in surface water generated by the derived scenarios are realistic and in line with the percentile set by risk managers, for all crops covered by the relevant scenario.

As stated in the previous paragraph, water flows in the growing system are considered the major determinant of emissions, whereas it is assumed that PPP emissions in general are proportional to the water discharges. Water flows are driven by plant transpiration and water uptake, as well as growers' choices regarding water supply versus crop water requirement and other management decisions. All influence water discharges and nitrogen emissions to surface water.

Risk managers asked for a small number of scenarios. Therefore, a logical step was to group crops into categories with similar discharges and nitrogen emissions and to choose a representative crop for each category. Initially, a division into two groups was made on the basis of transpiration rates, with the boundary value set at 600 mm. The transpiration rate was used as this is an influential factor in the water supply and consequently the supply of nutrients, the supply and accumulation of sodium and finally the discharge of nutrients. However, there was not sufficient distinction between two categories as crops in the same category showed substantial differences in emissions (see for example the results for rose and tomato in Table 3-4). Therefore, a further distinction was made to account for differences in the salt tolerance of the crops. A practical distinction level is a sodium tolerance of 4.5 mmol/l (see also Appendix A, which gives the sodium threshold limits above which discharge was permitted). Both category boundaries (a transpiration of 600 mm/yr and a sodium tolerance of 4.5 mmol/l) correspond to growers' expert knowledge. This results in a group of salt-sensitive and a group of salt-tolerant crops. Table 3-5 gives the resulting crop categories, important crops in each category (not limiting) and the total area per category.

Table 3-5 Soilless cultivated crop categories based on their transpiration level and salt tolerance.

Transpiration	**Salt (sodium) tolerance**	
	high (>4.5 mmol/l)	low (<4.5 mmol/l)
high (>600 mm/yr)	tomato, sweet pepper, cucumber, aubergine, bean, melon	rose, gerbera, anthurium
	3,000 ha	800 ha
low (<600 mm/yr)	lettuce, courgette, ficus, starting material vegetables, other vegetables	strawberry, orchid, phalaenopsis, carnation, amaryllis, bouvardia, iris, starting material flowers
	2,000 ha	700 ha

However, a few practical issues prevent adhering to this ordering principle. First, growing systems for the category 'low transpiration, low salt tolerance' are highly diverse and some are changing from open to recirculating systems. It is difficult to identify a representative crop and system for this category. Second, it would be not justifiable to treat tomato and sweet pepper, both important crops in terms of acreage and value, in the same way. Because of the substantially higher salt tolerance of tomato, discharge and emission patterns are different from those in sweet pepper.

Given these considerations, it was decided to develop four scenarios:

- 1/2 Two scenarios for the category 'high transpiration, high salt tolerance', with tomato and sweet pepper as representative crops, respectively.
- 3 One scenario for the category 'low transpiration, high salt tolerance', with ficus as the representative crop.
- 4 One scenario for the category 'low salt tolerance', with rose as the representative crop.

The scenarios are referred to as **tomato**, **sweet pepper**, **ficus** and **rose**, after the representative crops. Each of the relevant crops from the DTG list (see Appendix B) is assigned to one of the scenarios, on the basis of their transpiration rate and salt tolerance. The relevant scenario is linked to each crop in the software database (see Chapter 6).

Because of the specific growth conditions and PPP applications, the working group discussed the necessity of having one or more dedicated scenarios for nursery crops. In the regulation (Anonymous 2012), nursery crops are in the nutrient-emission categories for vegetables and flowering crops. Based on an analysis of water requirements and water management strategies, the working group considered that it is possible to assign each of the nursery crops to one of the four scenarios mentioned above. This meant that additional scenarios for nursery crops were not necessary. For a further overview of crops and crop characteristics see Appendix B.

3.3.3 *Scenario establishment*

Since soilless growing systems were introduced in the 1980s, the role of sodium has been widely discussed (see amongst others Sonneveld and Voogt 2009). Excessively high levels of sodium damage crops in terms of both quantity and quality. However, certain levels, dependent on the crop, can be tolerated and minimum levels are sometimes required for quality reasons (e.g. for tomato).

Sodium enters the recirculation system with the supply water and with fertilisers. Sodium leaves the recirculation system by crop uptake, discharge of recirculation water and filter rinsing water, and leakage from the system. If the sodium level exceeds the limit value, the grower will discharge the water and replenish with fresh water. However, in horticultural practice there are also other reasons for discharge. Growers may discharge recirculation water in accordance with their irrigation practice (for example always using a mixture of fresh, non-recycled water and recirculated water), undertake a daily flush of the system, and additionally flush when growth is hampered or when irregularities in the nutrient solution are detected. Discharge levels in practice were found to be higher than when calculated according to the physiological rationale of sodium-based management (see Section 3.1). Due to the growing awareness of water quality (with regard to nutrients as well as PPPs) in the Netherlands and political pressure, the practice of discharging recirculation water is changing towards lower annual discharges and emissions. Table 3-6 gives an overview of the relation between average nitrogen concentration, nitrogen emission norm and maximum volumes of drainwater to be discharged for the four selected crops.

Table 3-6 Relation between nitrate (mmol/l) in drainwater and nitrogen emission norm and amount of discharge (m^3/ha/yr).

	Tomato	**Sweet pepper**	**Rose**	**Ficus**
NO_3 supply (mmol/l)	13.9	16.1	5.6	14.1
NO_3 drain (mmol/l)	29.9	22.1	16.2	15.6
N in drain (kg/m^3)	0.42	0.31	0.24	0.22
N emission norm (2012–2014), (kg/ha/yr)	125	200	250	150
discharge (m^3/ha/yr)	300	650	1,050	700
N emission norm (2015–2017), (kg/ha/yr)	83	133	167	100
discharge (m^3/ha/yr)	200	425	700	475

It was decided to base the scenarios on both the need to comply with sodium levels (Table 3-4 and Appendix A) and additional reasons for discharging recirculation water (see above). The latter are translated into water discharge volumes based on expert judgement. In consultation with risk managers, the scenarios were developed in order to meet the nitrogen emission limits for 2015–2017 (corresponding to the last row of Table 3-6). This means that in the future new scenarios will be required, in order to keep up with the changing emission limits.

Analogously to current as well as proposed procedures for open field cultivation, it was decided to account for variability due to weather conditions. A two-step process was used to establish the scenarios. In the first step, calculations were performed for a series of 20 weather years and sodium-based discharge to gain insight into the variability of discharge. Then, in the second step, additional discharges due to crop and system management (e.g. filter rinsing) were added in order to achieve target emission limits (median values).

All the derived scenarios:

- use rainwater with a sodium level of 0.1 mmol/l as the primary water source;
- use RO water with a sodium level 0.1 mmol/l as the first additional water source and tap water with a sodium level of 1.5 mmol/l as the second additional water source.

Additional characteristics for the four specific crop groups are given in Table 3-7.

Table 3-7 Main characteristics of discharge regimes for the four classes of soilless cultivation water regimes.

Category	**1**	**2**	**3**	**4**
Associated crop	Rose	Tomato	Sweet pepper	Ficus
Crops in this class	gerbera, starting material, vegetables	cucumber, herbs	aubergine, strawberry	starting material, floriculture, other flower crops
Annual water demand	8250 m^3/ha	7670 m^3/ha	6530 m^3/ha	4640 m^3/ha
Threshold value sodium	4 mmol/l	8 mmol/l	8 mmol/l	6 mmol/l
Water supply - plant uptake ratio	1.5	1.25	1.25	1.5
Recirculation regime	no recirculation in first 8 weeks daily discharge to comply with the sodium threshold	no recirculation in first 4 weeks after planting	no recirculation in first 8 weeks after planting	occasional discharge based on management decision

The above choices are the input to the WATERSTREAMS model and result in four realistic water discharge regimes to be used in the PPP emission and scenario calculations. The weather data were taken from the weather station at Rotterdam airport.

3.4 Typical examples of water flows related to the scenarios

The principles described in the previous paragraphs determine to a large extent the water flows, but the flows are also influenced by fluctuations in weather conditions. Table 3-8 gives typical annual discharge volumes for the four scenarios. For example, 2003 was a year with little rain, and rainwater had to be supplemented by water from a source of lower quality. Consequently, there was more discharge.

Table 3-8 Annual discharge to surface water for the crops rose, sweet pepper, ficus and tomato. The quality of the various water sources was assumed to be the same for the four crops.

Year	**Annual discharge (m^3/ha^{-1}/yr^{-1})**			
	Rose	Sweet pepper	Ficus	Tomato
2000	661	388	425	215
2001	663	398	446	220
2002	761	392	440	214
2003	913	729	413	182
2004	611	366	435	207
2005	744	411	440	215
2006	702	477	408	187
Mean	722	452	429	206

Figure 3-1 gives an example of the dynamics of the quantity of fresh water in the rainwater collection basin for a 1 ha nursery. The total basin capacity is 1,500 m^3. The basin is full at the start of the year. Due to consumption and rather low rainfall, especially in March and April, the level in the basin declines to the minimal value of 100 m^3. Water from additional sources is regularly needed until the end of September

(Figure 3-2). Occasionally the RO capacity is insufficient and the second additional water source, tap water, is used. Surface water and groundwater are not used as water sources in this example. Lower water demand later in the season and high precipitation cause the level to go up again and reach capacity.

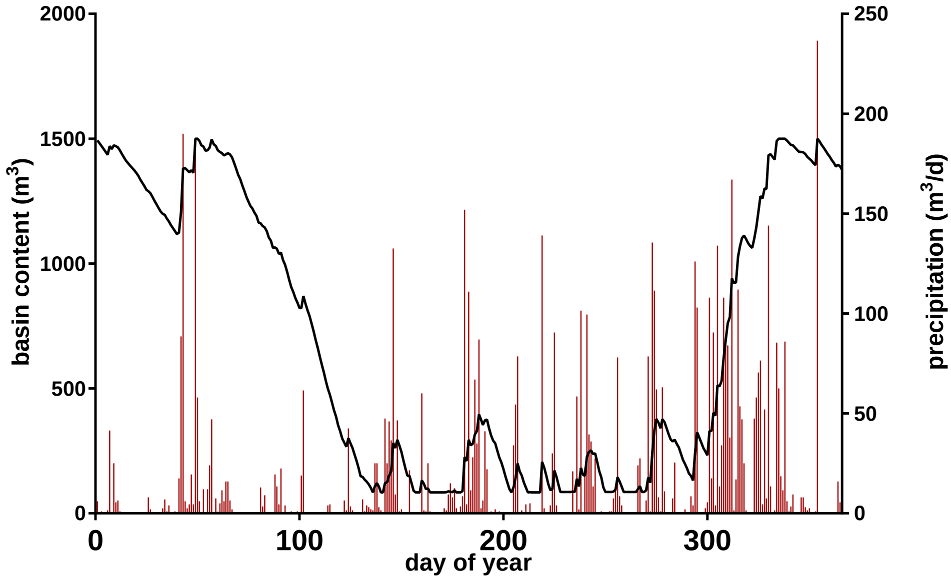

Figure 3-1 Example of the fresh water stock and its replenishment by rain.

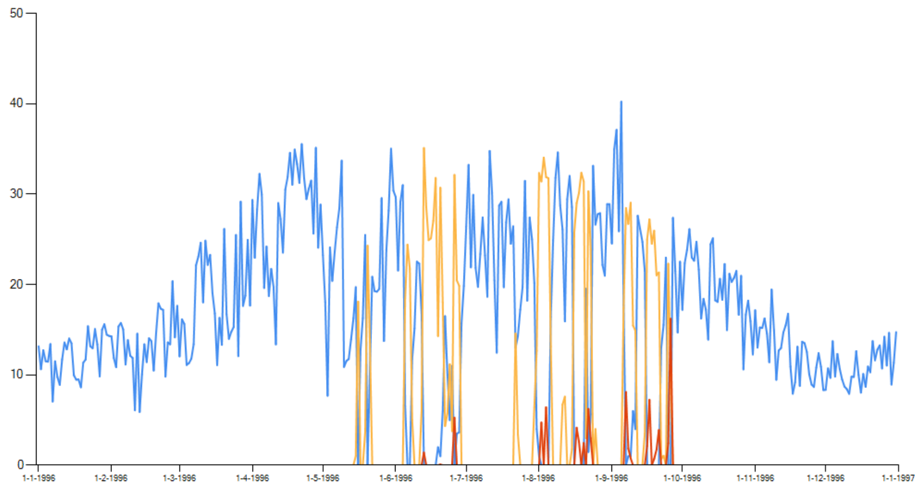

Figure 3-2 Example of water sources used during the growing season. Blue line: rain water; yellow line: reverse osmosis water; red line: tap water.

Figure 3-3 gives an example of the rising sodium concentration in the cultivation of roses. In this example, the secondary water source is RO water with a sodium content of 0.1 mmol/l. The sodium concentration does not reach the critical level of 4 mmol/l. Figure 3-4 shows an example of a discharge pattern that results from a strategy aiming at discharging small volumes at a time. There are almost daily discharges due to filter rinsing. Additional discharges of small volumes occur as well. The strategy complies with the nitrogen discharge limit of the crop.

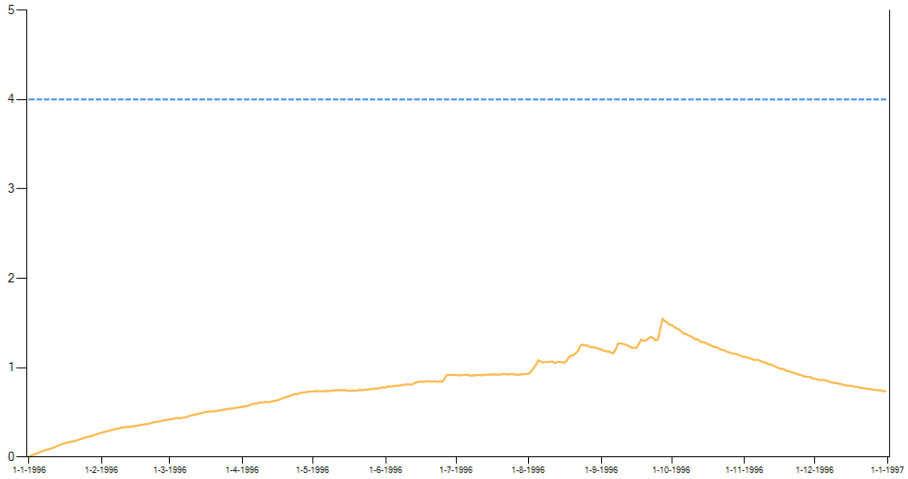

Figure 3-3 Example of the sodium level in the recirculating water in a rose cultivation. Sodium due to sodium concentration control does not occur.

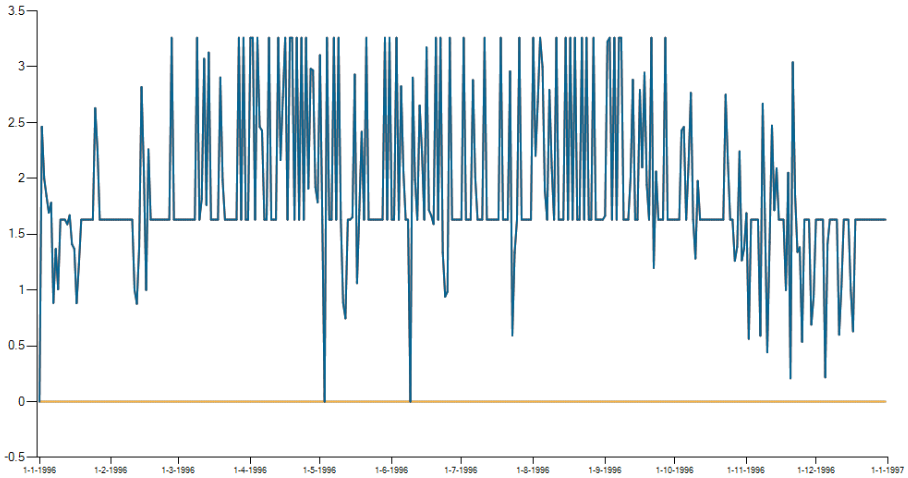

Figure 3-4 Example of a discharge (m^3) pattern. The yellow line at the bottom indicates that no discharge from the drainage tank occurs.

3.5 Conclusions on crop scenarios

Taking the national nutrient emission policy for greenhouses as a boundary condition, it was possible to develop scenarios for water flows in protected soilless growing systems. Essential to the approach were:

- No distinction between regions in the Netherlands;
- Identification of predominant growing systems: substrate systems with drip irrigation and ebb/flow irrigation;
- Selection of reference crops (tomato, sweet pepper, rose and ficus) based on the primary emission factors: transpiration and sodium tolerance;
- Combination of the sodium-based water model (WATERSTREAMS) for discharge calculations with additional realistic management measures to control crop growth, such as regularly partly refreshing the solution, discharging the solution

during the first few weeks after planting and discharging the solution based on observed growth inhibition;

- Linkage of nitrogen emission limits (in present legislation) to discharge flows: discharge volumes for tomato, sweet pepper, rose and ficus were, respectively, 200, 425, 700 and 475 m^3/ha/yr in 2015. These limits were applied to the 50^{th} percentile year, i.e. discharges will be lower in 50% of the years.

The approach led to four emission scenarios that collectively represent soilless cultivation in the Netherlands. The scenarios provide realistic worst case temporally variable water emission volumes that can be used to calculate PPP emissions to the receiving ditches.

4 Selection and parameterisation of the receiving surface water body

4.1 Receiving water bodies

Surface water is abundant in the Netherlands. Especially in the western part of the Netherlands, an extensive network of ditches discharges water from the polders via larger water bodies and rivers leading towards the sea.

Figure 4-1 Typical situation in the western part of the Netherlands; the greenhouses are situated directly next to surface water. Rainwater is collected for use in the growing system in the greenhouse.

The digital topographic map of the Netherlands (TOP10 vector) distinguishes between four categories of watercourses: (i) tertiary watercourses, which are small and/or temporarily dry, (ii) secondary watercourses, having a max. width of 3 m, (iii) primary watercourses, having a width of between 3 and 6 m and (iv) watercourses with a width of between 6 and 12 m. Massop et al. (2006) collected and classified the hydrological characteristics of Dutch watercourses, using the TOP10 vector map as a basis. The collected information included the width of the watercourse, the depth of the watercourse, bottom width, water depth and width at the water surface. The latter two ditch characteristics refer to a wet situation: the recorded water depth is assumed to be exceeded only 10% of the time.

Massop et al. (2006) observed a good correspondence between the geohydrological characteristics of the subsoil and the characteristics of watercourses. Twenty-two hydrotypes were distinguished, each having distinct geohydrological characteristics (Massop et al. 1997). For each combination of hydrotype and ditch category, they collected ditch characteristics through field inventories and calculated median values and standard deviations. The ensemble of all median ditch properties together generates a standard ditch profile. By coupling the map of hydrotypes and the watercourse categories (TOP10 vector), a spatial distribution of ditch profiles was derived, with the length of watercourses per category for each hydrotype.

The geographical location of horticulture growers was derived from the GIAB CBS geographical information database (Naeff and Smidt 2009). For each grower this database gives the postal address, the greenhouse horticulture area and the crops grown. From this, the area per type of cultivation (soilless or soil-bound) was derived. By combining the spatial distribution of ditch profiles and the geographical location and characteristics of the growers, a distribution of ditches that potentially receive water from greenhouse horticulture was derived.

In Table 4-1, the area cultivated with soilless crops is shown for the relevant hydrotypes. The hydrotypes Westland C, D and DC cover the largest areas of soilless crop cultivation. These hydrotypes are found mainly in the western part of the Netherlands.

Table 4-1 Area of soilless crops per hydrotype (only the hydrotypes with an area of >30 ha are shown). The names of the hydrotypes are given in Dutch (for explanation see Massop et al. 2006).

Hydrotype	Area of soilless crop cultivation (ha)	Percentage of total soilless crops
Betuwe-komgronden	108	2
Betuwe-stroomruggronden	137	2
Dekzand profiel	453	7
Duinstrook	498	8
Nuenengroep profiel	347	5
Open profiel	226	4
Peeloo profiel	68	1
Tegelen/Kedichem profiel	260	4
Westland-C-profiel	1430	22
Westland-D-profiel	983	15
Westland-DC-profiel	932	15
Westland-DH-profiel	438	7
Westland-DHC-profiel	121	2
Westland-H-profiel	250	4
Keileem profiel	89	1
Singraven-beekdalen	92	1

4.2 Water body selection

The aim of the procedure for selecting the receiving ditch was to select a ditch that could be regarded as representative of greenhouse-discharge-receiving ditches in the Netherlands.

Ditch volume and flow velocities are considered key parameters that explain most of the variation in PPP concentrations after an immission (Westein et al. 1998). Both vary over time, mainly due to weather variability. The lineic volume of a ditch (the volume of water per unit length) is a key determiner of the spatial variability of concentration in ditches. The flow velocity is a key determiner of the temporal variability of ditch concentrations. Other parameters that affect the concentrations in the water are the organic matter content of the sediment and temperature. As the spatial variability of organic matter content in the sediment in Dutch ditches is unknown, this factor is not considered in the scenario selection. Neither is temperature, which has less effect on PPP concentration than the other factors.

The receiving watercourse was selected by ranking the ditches according to their lineic volume and weighting them according to their abundance. Figure 4-2 shows the cumulative distribution of the ditches that potentially receive water from greenhouse horticulture, ranked according to their lineic volume. The 50th percentile (median) ditch has a lineic volume of 570 L m^{-1} and refers to the Westland C hydrotype, a watercourse belonging to category ii. Ditches and streams wider than 6 m (i.e. category iv) are excluded from the population, because they usually do not receive discharge water from greenhouses. Figure 4-3 shows the mean values of the ditch characteristics that belong to a Westland C type, secondary ditch. This ditch type is also used in the parameterisation.

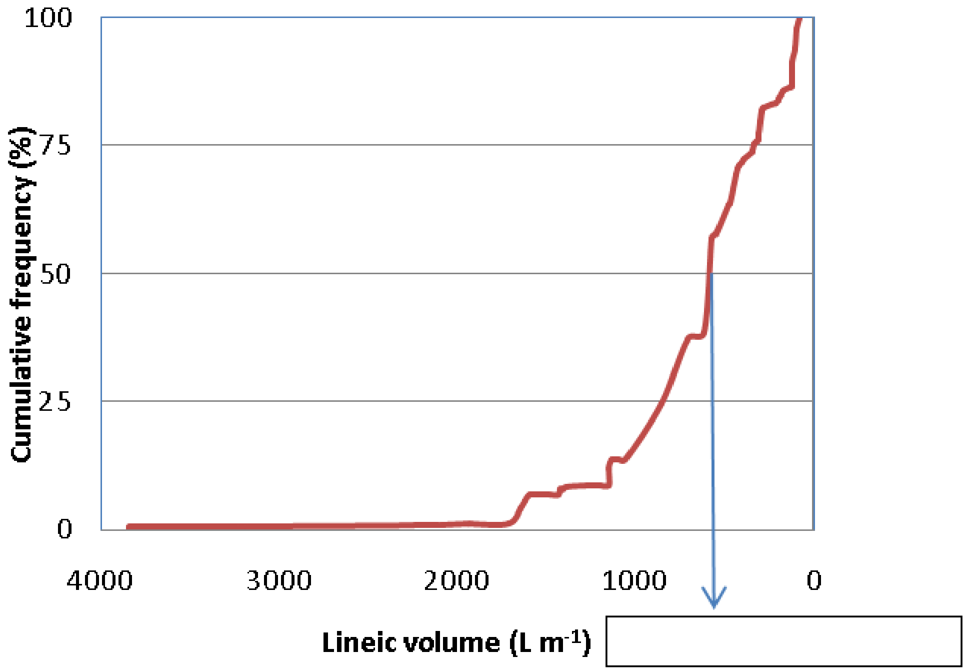

Figure 4-2 Cumulative frequency distribution of all ditches that potentially receive water from soilless greenhouse horticulture cultivation, ranked according to their lineic volume. The 50th percentile has a lineic volume of 570 L m^{-1}.

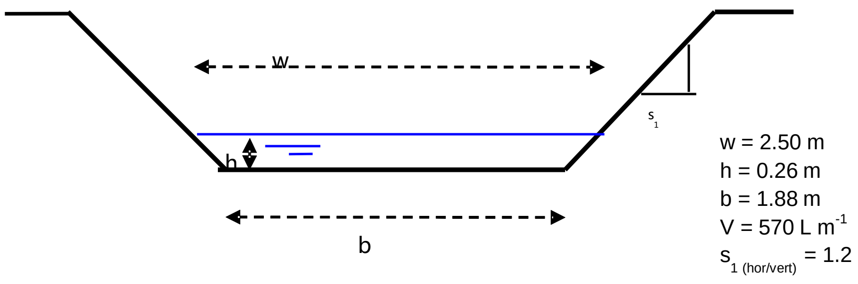

Figure 4-3 Dimensions of the Westland C ditch, where w is the width of the water surface, h is the water depth, b is the width of the bottom of the ditch, s_1 is the side slope (horizontal/vertical), and V is the lineic volume of the water in the ditch.

4.3 Flow velocities in the selected water body

To obtain realistically temporally variable water flow velocities, an existing calibrated hydrodynamic model was used, i.e. the model (1D/2D SOBEK Rural) of the Oude Campspolder, a polder situated in the Delfland control area between Rotterdam and The Hague. The detailed calibrated hydrodynamic model provided daily water discharges and water depths for 137 watercourse segments within the Oude Campspolder model for the period 2000–2006. The working group is greatly indebted to the Waterboard of Delfland for providing the model.

The velocity distribution of the water bodies within the Oude Campspolder was assessed and a segment was selected that had the same characteristics as the hydrotype Westland C, while care was taken that the segment velocities were in line with the overall distribution of velocities within the polder. The rationale behind this approach was that the flow velocities within the Oude Campspolder were representative of similar Dutch ‘greenhouse’ ditches.

The methodology followed was that described in Wipfler et al. (2015a). For both the soilless cultivation scenarios and the soil-bound cultivation scenario, the same Westland C ditch was selected and parameterised. Hence, the receiving ditch was the same for all scenarios. See Wipfler et al. (2015a) for a detailed description of the Oude Campspolder hydrodynamic model as well as for an explanation or the ditch selection procedure.

The water fluxes in the selected ditch segment of the Oude Campspolder are shown in Figure 4-4. The available time series is over the parameterised period, i.e. 1 January 2000 to 31 December 2006. These seven years of daily water fluxes were applied as upper boundary conditions to the simulated ditch.

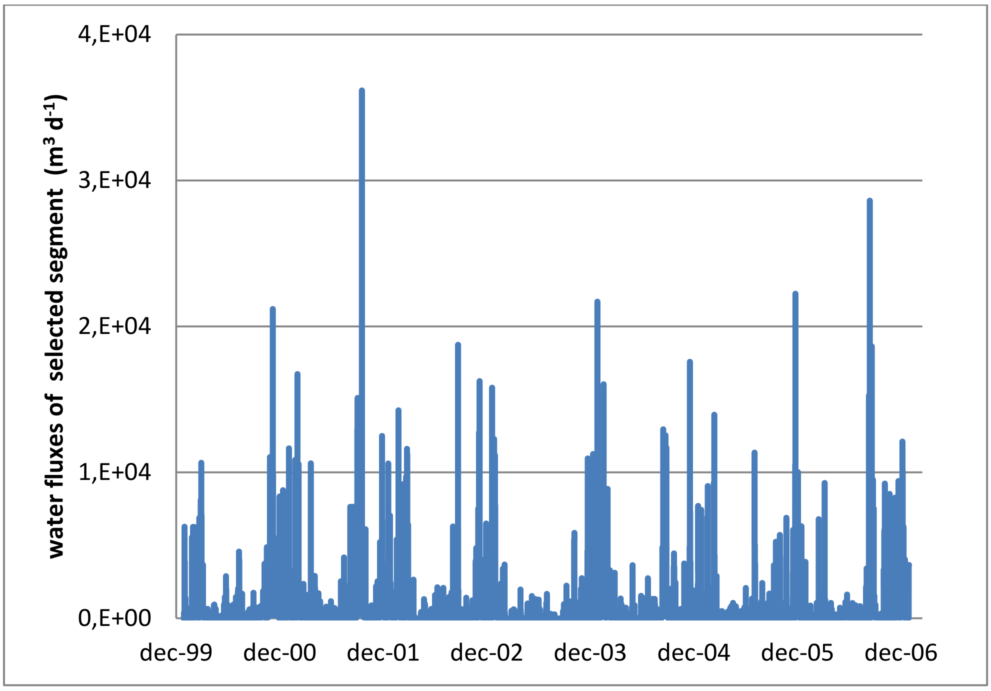

Figure 4-4 Water fluxes of segment 1. These fluxes are used as upper boundary conditions in the simulation.

4.4 Further parameterisation of the water body model

PPP fate in the water body was simulated with the TOXSWA model (TOXic substances in Surface WAters, Adriaanse 1996, Beltman et al. 2014). The model was developed to calculate PPP concentrations in surface water and sediment. TOXSWA considers transport, degradation, the formation of transformation products, sorption to sediment and suspended solids, and volatilisation. The transformation rates cover the combined effect of hydrolysis, photolysis and biodegradation. Transformation and volatilisation are assumed to be temperature-dependent. Sorption to sediment and suspended solids is described with the Freundlich equation.

4.4.1 Conceptual model

PPP concentrations are to be calculated in a ditch with a length of 100 m. However, based on experience, we considered a ditch with a length of 400 m to accommodate for a weir 300 m downstream. The dimensions are constant along the ditch and equal to the Westland C ditch; the dimensions of the ditch are shown in Figure 4-3. The simulated ditch consists of a water layer and a sediment layer. Exchange between the two layers is only via diffusion.

The (time-varying) external upstream water flux was taken from the Oude Campspolder model and set as an upper boundary condition to the model. No discharge was considered from external fields draining into the ditch except greenhouse discharges. Precipitation and evaporation were not considered by the model. The water leaves the ditch via a weir, located at the lower boundary of the ditch. The bed-slope over the length of the ditch was assumed to be zero, which is consistent with 91% of the slopes observed in the Oude Campspolder. The non-stationary velocity fluxes within the water body were calculated by solving the water balance equation over the water body. The discharge–water level relationship (Q-h) was approximated by assuming that (dQ(x,t))/dx is constant over the length of the ditch, i.e. the water level is constant over the length of the ditch. For further information on the method used see Opheusden et al. 2011.

The applicability of the approximation was assessed by comparing the discharge calculated with the approximation to results obtained with a non-stationary model. The non-stationary model solves the water conservation equation and the momentum conservation equation simultaneously. The assessment revealed that the approximation is sufficient, especially for low flow situations (Wipfler et al. 2015a).

The discharge from greenhouses to the ditch was simulated as a point source at the upper boundary of the ditch by adding the discharge volume flux to the upstream water flux of the water layer. Hence, the discharged volumes were supposed to be additional to the 'Oude Campspolder' fluxes. The PPP mass that is discharged by the greenhouse was simulated as an incoming mass flux at the upper boundary of the ditch. No other sources of PPP were considered.

In TOXSWA, a PPP within the water layer is subject to convective and dispersive transport, volatilisation, degradation, sorption to suspended material, and exchange with the sediment layer via diffusion. The substance mass balance was solved over the first 150 m of the evaluation ditch – 100 m for calculation of the ERC and 50 m to eliminate the boundary effect at the lower boundary resulting from neglecting dispersion.

Exchange with the sediment layer occurs via diffusive transport at the water–sediment interface. The TOXSWA sediment layer has a thickness of 10 cm and is characterised by bulk density, porosity and organic matter content. These parameters were assumed to be constant over the sediment layer, i.e. there is no gradient either along or perpendicular to the ditch. Within the sediment layer, the PPP concentration may vary along and perpendicular to the ditch due to diffusive transport and adsorption. It was assumed that there is no exchange between sediment and groundwater (Neumann boundary condition).

The number of ha of greenhouses that may discharge into a ditch depends on the greenhouse density and the total length of the ditches that potentially receive discharge from greenhouses. The area of greenhouses and the corresponding ditch length have been studied for six high-density greenhouse areas in the Netherlands. The assessment revealed that for the studied areas there is approximately 100 m of nearby ditch per ha of greenhouses. The working group did not have information regarding crop treatment in the area upstream of a discharge point. It was assumed that the upstream area of the ditch is untreated and the horticultural area of each grower is 100% treated, i.e. 1 ha of treated crops discharge to the 100 m of evaluation ditch.

4.4.2 *Weir characteristics*

At the upper boundary of the model, water flows over a weir. Weir properties consist of the weir width and the height of the weir crest. In conformity with FOCUS (2001) and the field crop scenario (Tiktak et al. 2012) the width of the weir was set at 0.5 m. The height of the weir crest has been calibrated such that the lineic volume of 570 L m^{-1} (see Section 4.2) is exceeded only for 10% of the time (in line with the general design of ditches in the Netherlands). The calibrated weir crest height for the evaluation ditch was 0.16 m.

4.4.3 *Sediment and suspended solid properties*

For the sediment and suspended solid properties, the values derived for the evaluation ditch for field crops (Table 4-2) were used. Properties are based on values from available databases. Macrophytes are assumed to be absent. For further details see Tiktak et al. (2012).

Table 4-2 Sediment and suspended solid characteristics.

Characteristic	**Value**
concentration of suspended solids in the water layer	11 g m^{-3}
mass fraction of organic matter in suspended solids	0.090 kg kg^{-1}
sediment layer depth	0.1 m
mass fraction of organic matter in sediment	0.090 kg kg^{-1}
bulk density of the sediment	800 kg m^{-3}
porosity	0.68 m^3 m^{-3}
tortuosity	0.56 (-)

4.4.4 *Temperature*

The TOXSWA model uses monthly averaged values for the water temperature in the ditch to calculate the effect of temperature on the rate coefficients for volatilisation and transformation of PPP. It was assumed that the temperature in ditch water equals the air temperature. Mean monthly temperatures were calculated on the basis of the daily minimum and maximum air temperatures of the de Bilt weather station provided by the KNMI.

4.5 Coupling of greenhouse scenarios to the parameterised ditch

From the hydrodynamic model only seven simulated years of velocity fluxes were available. As a consequence, simulations were done for only seven years. These years were assumed to be sufficient to derive the considered percentile.

4.6 Conclusions on ditch selection

Using the geographical information of the TOP10 map combined with characteristics of water bodies by Massop et al. (2006), a 50th percentile water body was selected, which is of type Westland C, secondary ditch.

The receiving water body had a length of 150 m with a weir downstream. The incoming (upstream) water flow was taken from a selected segment of the calibrated hydrodynamic model of the Oude Campspolder, situated in the western part of the Netherlands.

The TOXSWA surface water fate model was parameterised. The parameterised model enables the calculation of the (hourly) PPP water concentrations in water averaged over 100 m of water body due to discharge from soilless horticulture. The discharge area was set to 1 ha. From the time series of water concentrations the Predicted Environmental Concentration (PEC) can be derived, being either the 50th percentile or the 90th percentile annual peak.

5 Substance fate models for substrate cultivations

The risk assessment methodology as described in this report requires three models to describe the fate and behaviour of PPP in the greenhouse soilless growing system and, after discharge, in surface water. For the latter compartment, the TOXSWA model (Adriaanse 1996, Beltman et al. 2014) was chosen (see also Chapter 4).

The dynamic water flows in the greenhouse, i.e. in the growing system, basin and storage tanks, and the discharges (timing and volumes) to the surface water are described by the WATERSTREAMS model (Voogt et al. 2012). Temperatures in the greenhouse system are also calculated by the WATERSTREAMS model. Both the water flows and the temperatures generated by the WATERSTREAMS model are based on the typical water management and discharge regimes per crop class discussed in Section 3.3 and are input to the substance fate models. The weather data for the WATERSTREAMS model was taken from the weather station at Rotterdam airport. The model provided three-hourly water flows to the Substance Emission Model. The water flows were: plant evapotranspiration, filter discharge, discharge due to sodium control and condensation water fluxes. The plant evapotranspiration–irrigation ratio was also given.

The fate and behaviour of substances in the greenhouse system are described by the Substance Emission Model. As described in Chapter 3, a major distinction can be made in soilless cultivation between systems with drip irrigation and systems with ebb/flow. These systems require different approaches to the calculation of the fate and behaviour of the substances in the systems, dependent on the application of the PPP. Therefore, three substance fate models were developed:

1. Application of the PPP with the nutrient solution. This model is for all crops, independent of the irrigation system.
2. Spraying or fogging the PPP on the crop canopy for systems with a drip irrigation system.
3. Spraying or fogging the PPP on the crop canopy for systems with an ebb/flow system.

The models have in common that degradation in the various water tanks and growing system is described according to first order processes, influenced by the temperature of the water. Degradation may result in metabolites, which are subject to further removal, dependent on substance characteristics. Removal of the PPP, and metabolites, from the growing system by plant uptake may occur, dependent on the octanol/water partitioning coefficient. The three models differ in 1) the way the PPP enters the greenhouse recirculation water, 2) the distribution of the PPP over water phase, plants and substrate, 3) the exchange with the air compartment and 4) the sorption to surfaces in the greenhouses. In the first model, where all the PPP is applied to the nutrient solution, exchange with the air is considered not to occur due to the plastic slab cover and low saturated vapour pressures of PPP applied in that way. In models 2 and 3, substances in the greenhouse air compartment are subject to exchange with outside air, dependent on the ventilation rate of the greenhouse. Details of the models are given in Appendices C–E.

Discharge volumes and discharged PPP mass for the parent as well as for metabolites formed in the system, are input into the TOXSWA model on an hourly basis. As described earlier in this report, the discharges are received at the upper boundary of the model ditch. Concentrations are calculated over a length of 100 m downstream of the discharge point. The model is sensitive to the sediment discretisation for substances with large K_{OC}, i.e. the discretisation should be refined for K_{OC} larger than 1e6 dm^3/kg. This is done automatically by the software package GEM (Chapter 6).

6 The GEM software package

6.1 The package

The Greenhouse Emission Model (GEM) software package consists of:

- A graphical user interface (GUI) used to define runs and visualise results;
- An add-in database (SPIN) that enables the input and storage of substance data. This database not only is attached to GEM, but serves the same purpose for other exposure models as well.
- Databases with underlying information on the various crop and ditch scenarios. The scenarios for soil-bound greenhouse cultivations (Wipfler et al. 2015a) are included as well.
- The models that perform the necessary calculations:
    - The WATERSTREAMS model (Voogt et al. 2012) for calculating water flows in the system as well as the amounts and timing of discharges (see also Chapter 3);
    - The substance models for calculating the fate of the active substance and metabolites in the greenhouse system. The system selects the appropriate model based on the selected crop and application type;
    - The PEARL model (Leistra et al. 2001, Tiktak et al. 2000) for calculating fate and behaviour in soil-bound cultivations and drainage to surface water;
    - The TOXSWA model (Adriaanse 1996, Beltman et al. 2014) for calculating the fate of the substance (including metabolites) in the ditch (the surface water system).

The software is tested to run under Windows operating systems VISTA, 7 and 8, but probably will run under 10 as well.

Details on operating the system can be found in Wipfler et al. (2015b), van Kraalingen et al. (2013) and Wipfler (2014).

6.2 User defined input

The scenarios contained in GEM are largely predefined. Therefore, limited input is required before a run can be made. The user starts the GUI of GEM and provides the necessary information and selections for constructing an assessment scenario. When the GUI is started, a screen like the one in Figure 6-1 opens. This screen is used to enter general information on the assessment and to select a crop and a substance.

Pressing the crop selection button opens a screen like the one shown in Figure 6-2. The screen shows the items in the DTG list, arranged in four levels. Crop groups with a green arrow contain one or more crops that are available for selection. Crops are selected at the lowest (4^{th}) level by checking the selection box. Only one crop can be selected at a time. When a crop is selected, the necessary settings for the crop water requirements and other growth conditions are automatically selected (see Chapter 3).

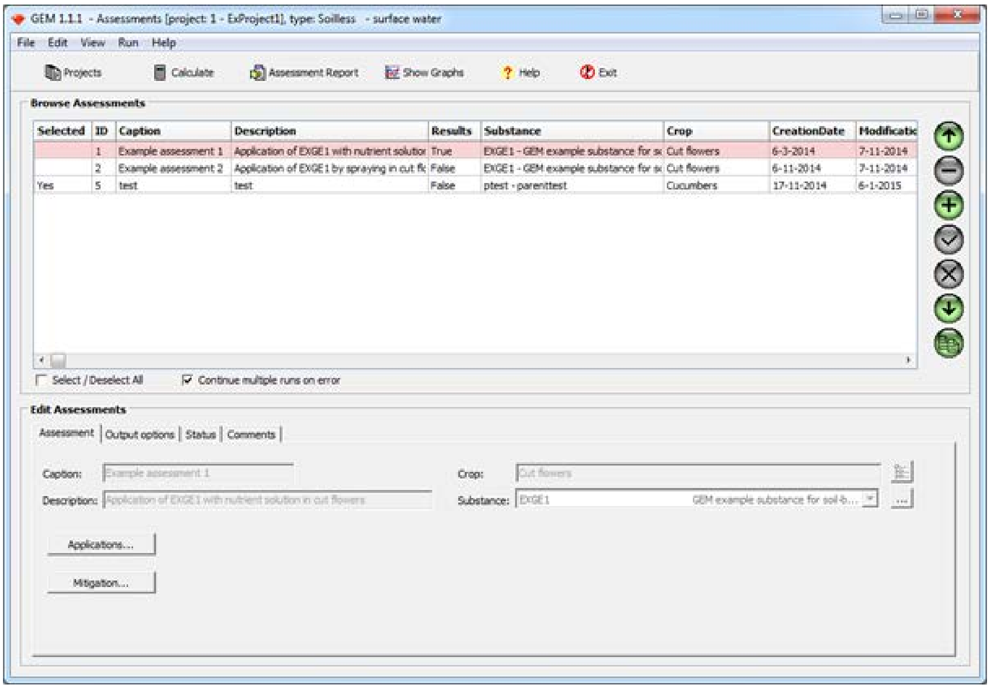

Figure 6-1 Main (assessment) screen of the GEM GUI.

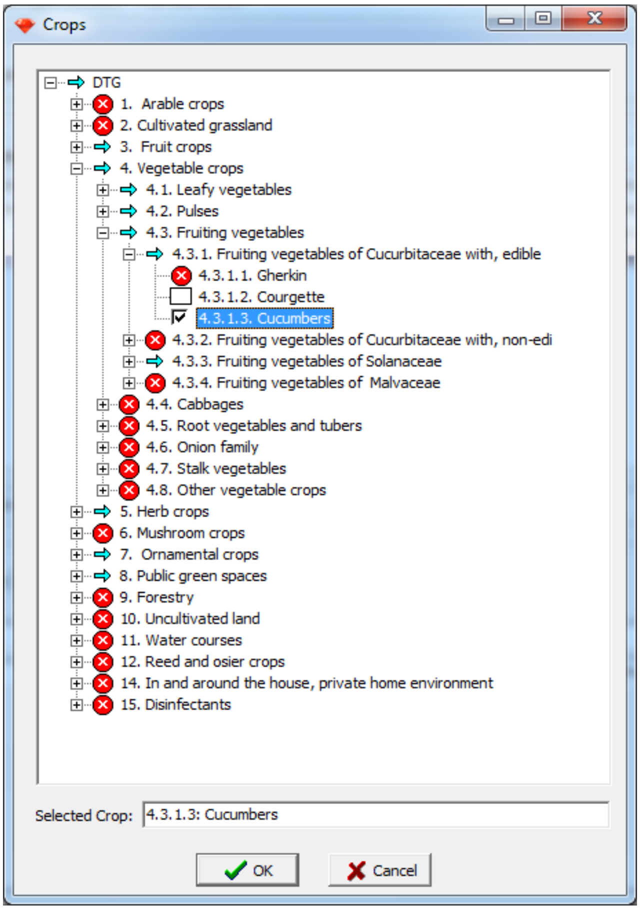

Figure 6-2 Selection of the crop.

If the substance is not yet in the SPIN database, the ellipsis button '…' (Figure 6-1, right hand side) opens the SPIN GUI (Figure 6-3), with which the new substance can be specified. Physicochemical and fate properties are entered using the appropriate forms (general – crop processes) and their sub-forms. Opening SPIN from GEM enables all forms necessary to specify input required for GEM calculations, while leaving other forms disabled.

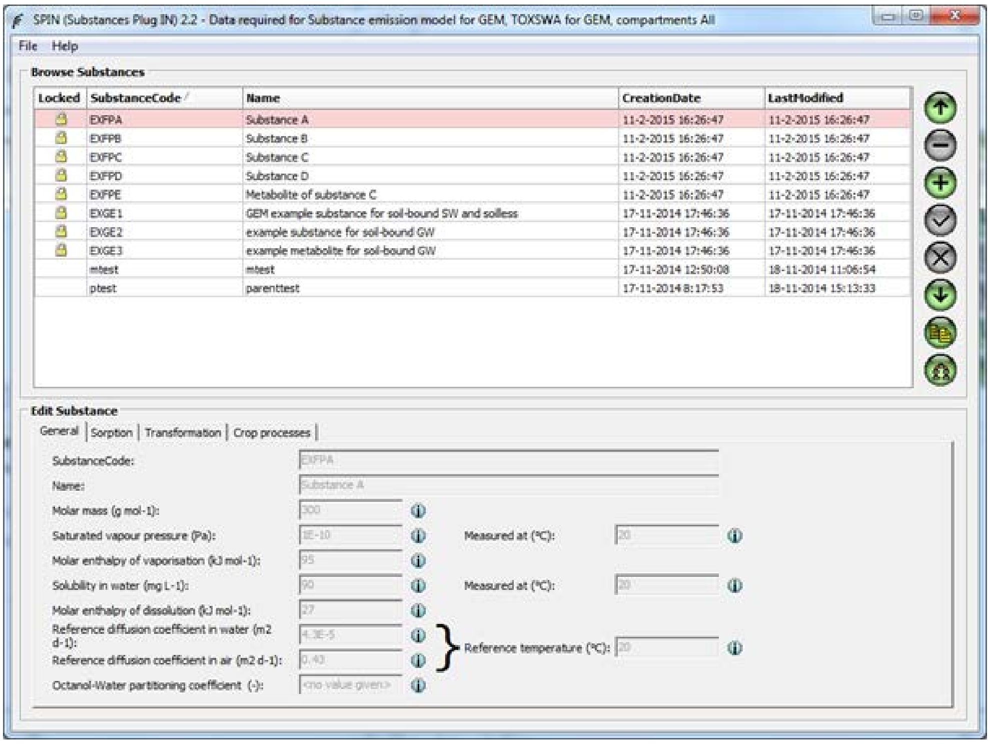

Figure 6-3 Opening screen of SPIN.

A number of greenhouse-specific substance properties are required to be filled in:

- The equilibrium sorption coefficient K_{OM} (L kg^{-1}) to substrate (specific for pot plants). If no specific information is available it is suggested to use the sorption coefficient for soil.
- Half-life in recirculation water (d) and the temperature at which it was measured. If no specific information is available it is suggested to use the $DegT_{50}$ for hydrolysis.
- Molar activation energy (kJ mol^{-1}) for the degradation in recirculation water. It is suggested to use a molar activation energy of 75 kJ mol^{-1}.
- Half-life in the disinfection tank (d) and the temperature at which it was measured. If no specific information is available it is suggested to use the $DegT_{50}$ for hydrolysis.
- Half-life on the greenhouse floor (d). If no specific information is available it is suggested to use 100 d.
- Half-life in substrate (d). If no specific information is available it is suggested to use the $DegT_{50}$ for degradation in soil.
- Half-life in greenhouse air (d) and the temperature at which it was measured. It is suggested to use the half-life in air when available; otherwise a half-life of 100 d can used.

- Molar activation energy (kJ mol^{-1}) for the degradation in greenhouse air. It is suggested to use a value of 45 kJ mol^{-1}.

From the main screen, the user can reach the applications screen (Figure 6-4). This screen is used to define the applications (one or more) of the PPP to the crop.

If water is discharged from the growing system via a water purification system (e.g. active carbon filter, UV or ozone treatment system), the user can specify the removal efficiency of the system by pressing the 'Mitigation' button and entering the removal fraction. The emissions to the surface water will then be lowered by the specified fraction. The reduction of PPP is applied to the discharge of both recirculation water and filter cleaning water.

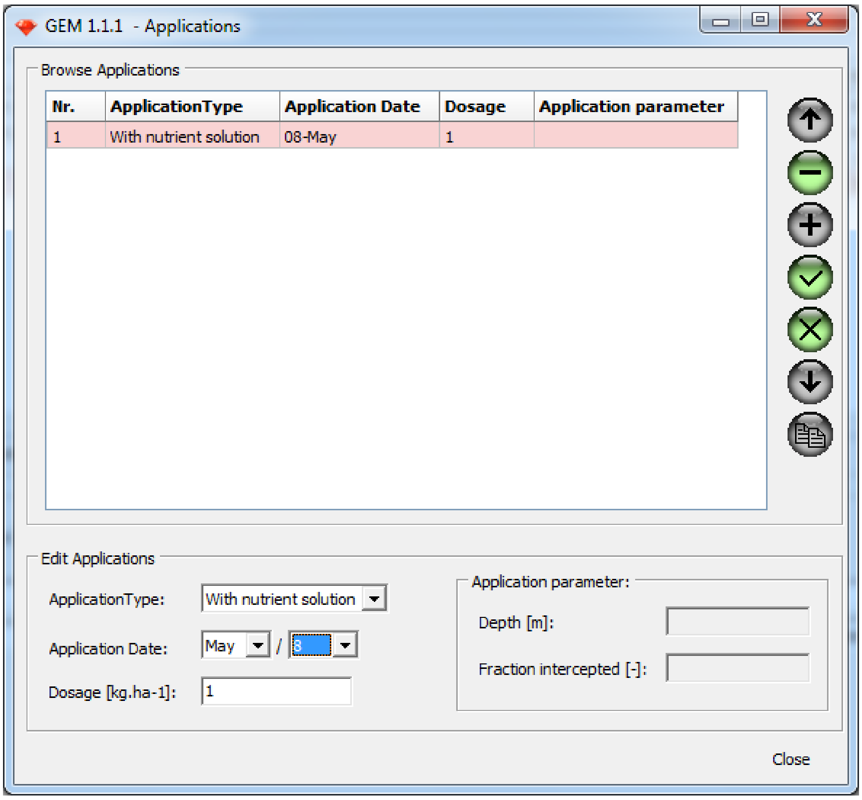

Figure 6-4 GEM applications screen.

Having entered the data necessary for the calculations, the user can specify the required output using the screen shown in Figure 6-5. Standard output includes maximum concentration in the ditch as well as maximum Time Weighted Average (TWA) concentrations over 7 and 21 days. If graphical output is required, the appropriate square has to be checked. Up to 8 additional Time Weighted Average (TWA) concentrations can be specified using the TWA...-button; both the duration and the period for which they are calculated can be set by the user.

Finally, the user can specify the target percentile year, i.e. the year that will be selected from the available calculated output. For example, entering 50 will select the year ranking median in the calculated maximum concentrations. Which value to enter depends on risk management decisions.

Pushing the ‘calculate’ button starts the selected assessments.

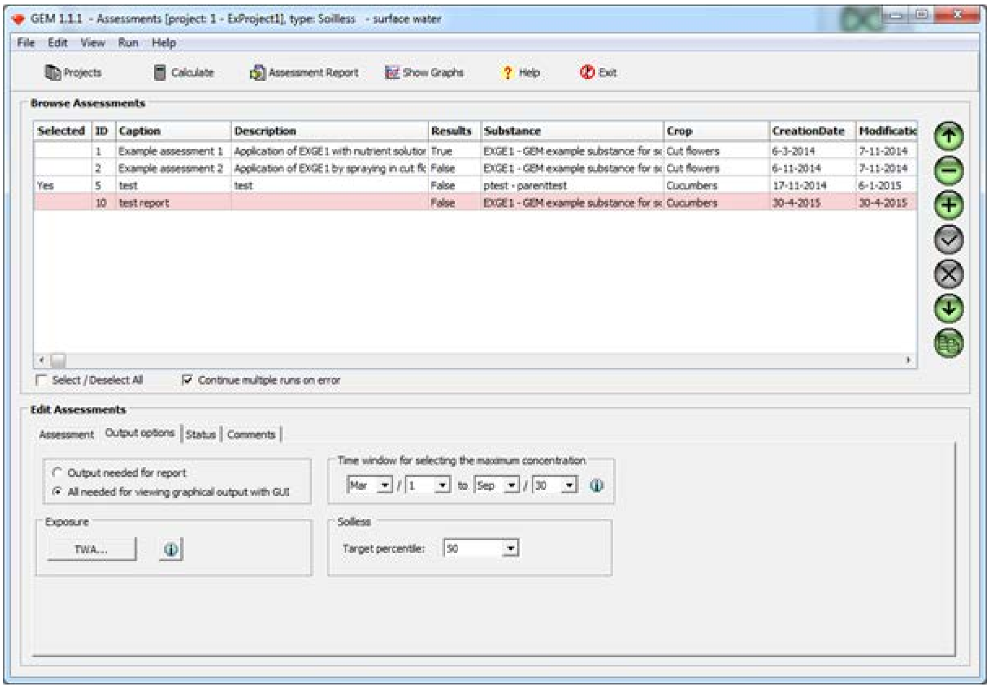

Figure 6-5 GEM output definition screen.

After the calculations have finished, the user can access the assessment report and graphical output, the latter dependent on the output specifications. The output report essentially contains:

- The model names and version numbers used in the calculations;
- The values of the main input parameters;
- The output of the various models used in the calculations. Part of the output is easily accessible via the GUI;
- The final results, i.e. the required concentrations (peak and TWAs) in the evaluation ditch.

If the box for graphical output has been checked, the results can be viewed as graphs via the Show Graphs button. The user can select from various types of graph, such as a graph of concentration in surface water versus time (Figure 6-6). There are several options for exporting the results.

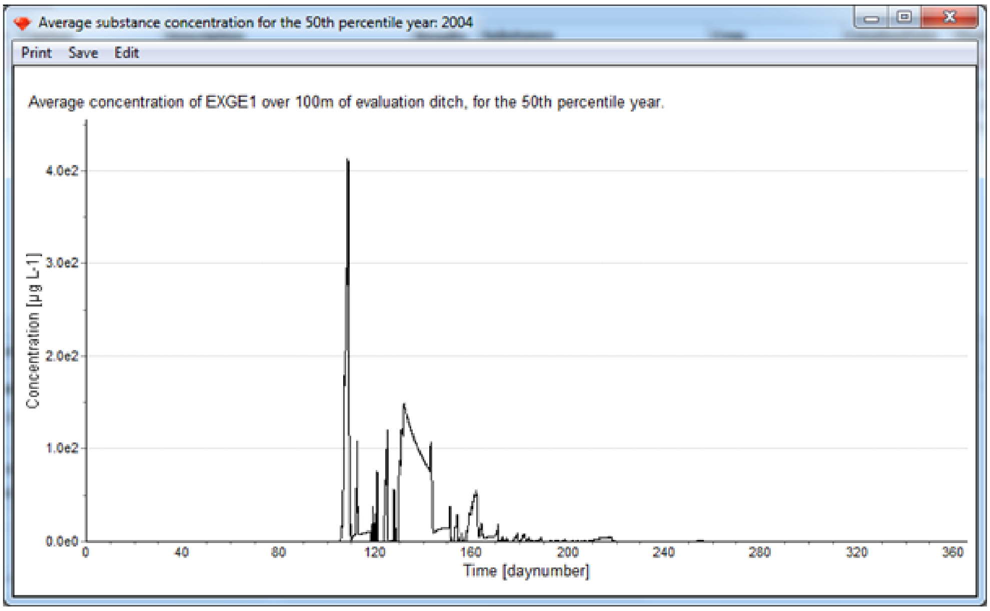

Figure 6-6 Graphical output example. Concentration versus time in the evaluation ditch.

7 Conclusions and recommendations

7.1 Conclusions

This report describes the exposure scenarios that were derived for the environmental risk assessment of plant protection products (PPPs) applied to crops grown on substrate in the Netherlands. Four crop scenarios were developed, together covering all soilless crops in the Netherlands. Each soilless crop is assigned to one of the four scenarios, depending on the crop's water requirement and its tolerance to sodium accumulation in the recirculating nutrient solution.

Crop scenarios were developed on the basis of surveys about available systems and water sources and nutrient emission limits set out in national legislation. Information was translated into crop management strategies such that nutrient emission limits for 2015–2017 will be met in approximately 50% of the years. The two main discharge routes considered were discharge due to sodium control measures and discharge of filter cleaning water.

A simplified set-up of the growing systems was used to develop fate and behaviour models of PPP substances applied to the crops. Both water reservoirs and the water contained in the growing system itself are considered well mixed systems from which substances dissipate with the water flow and degrade according to first order processes. Except in the potting systems, sorption of substances to substrate is taken to be negligible. PPP may be applied with the nutrient solution or via spraying, fogging or a low-volume mister.

Emissions from the greenhouse soilless systems enter an edge-of-field ditch. The dimensions of the ditch used in the scenarios were obtained by combining national databases of watercourses and greenhouses and selecting a representative watercourse (50^{th} percentile). Further parameterisation of the ditch was hampered by the poor availability of data on water flow dynamics in ditches, which explain most of the variation in surface water concentrations after emission. This was solved by using the velocity fluxes of a detailed and calibrated hydrodynamic model applied to a dense greenhouse area.

The exposure scenarios and models for performing environmental risk assessments are incorporated into an easy-to-use software package, GEM. The endpoints of the exposure calculation, i.e. the target protection percentile can be set to the 50^{th} or 90^{th} percentile by the user. Emission reduction due to end-of-pipe mitigation measures can also be taken into account.

7.2 Recommendations

The model for calculating emissions from greenhouse cultivations uses a simplified layout of such cultivations as well as approximations of the water flows within the system. It is recommended that experiments are performed to test in practice whether the model sufficiently approximates reality. Furthermore, some processes regarding fate and behaviour of PPP in the system (e.g. sorption to the substrate) have been neglected as it was assumed that these processes would have limited influence on the emissions. Experiments may reveal whether these assumptions are correct.

The scenarios for the four crop groups described in this report are based on expert judgement, taking account of the given limits for the emission of nutrients for the year 2015. The current policy regarding emissions of nutrients to surface water is to stepwise lower the limits to the final values, to be reached in 2023. In order to comply with the limits, growers will change their water and nutrient management strategies and, as a consequence, the scenarios will need adaptation in order to keep up with changing practices.

Future scenarios, compliant with forthcoming emission limits, can again be based on expert judgement, but more information on water use and discharge and (other) crop management practices should preferably be gathered and used.

The working group provided suggestions for ways of quantifying the greenhouse-specific substance properties, based on current dossiers. The proposed methodology allows for the refinement of substance input parameters, i.e. specific information on the half-life of a substance in recirculating nutrient solution and/or in surface water can be introduced. It might be useful to develop a tiered approach to environmental risk assessments concerning the use of PPP on (soilless) greenhouse crops. Such an approach will probably be useful only after experience has been gained with the methodology.

This report is about the risk assessment of the application of PPP to substrate cultivations in greenhouses. There are also non-covered substrate cultivations. The risk assessment of the use of PPP on these 'open air' substrate cultivations cannot be performed with the methodology described in this report as, for example, water regimes and temperatures are quite different. Also, the current methodology for 'open field applications' is not suitable for these cultivations as no soil is involved. Development of appropriate scenarios is recommended.

Although growing conditions in high-tech greenhouses are controlled to a large extent, soilless cultivations outside the Netherlands may not be adequately represented by the given scenarios. This is partly due to compulsory crop and water management practices in the Netherlands and national nutrient emission limits. Climatic conditions influence both the availability of water and crop management and may therefore have a large effect. It should therefore be carefully checked whether these scenarios can be used in other countries. Most probably, country-specific scenarios need to be developed.

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Glossary and abbreviations

BBCH	growth code for plants
CBS	Centraal Bureau voor de Statistiek, Statistics Netherlands
Ctgb	College voor de Toelating van Gewasbeschermingsmiddelen en Biociden, Board for the authorisation of plant protection products and biocides
DTG	Definitielijst Toepassingsgebieden Gewasbeschermings-middelen, List of crops (and other application areas) to which plant protection products can be applied
Drainwater	Excess irrigation water flowing from the growing system. Drainwater is usually reused.
ERC	Ecotoxicological Relevant Concentration
EEC	European Economic Community
EFSA	European Food Safety Authority
Emission	technical term signifying the transfer of a substance over a boundary
ERA	Environmental Risk Assessment
EU	European Union
FOCUS	FOrum for the Co-ordination of pesticide fate models and their USe
GEM	Greenhouse Emission Models (software program)
GH	greenhouse
GIAB	Geografische Informatie Agrarische Bedrijven, Geographical Information on Agricultural Enterprises
GLAMI	Werkgroep Glastuinbouw en Milieu, working group on greenhouse horticulture and environment
GUI	graphical user interface
LAI	Leaf Area Index
KNMI	Koninklijk Nederlands Meteorologisch Instituut, Royal Netherlands Meteorological Institute
MS	member state of the European community
NAP	Normaal Amsterdams Pijl (approximately average sea level)
PEARL	Pesticide Emission Assessment and Regional and Local scale, model
PPP	plant protection product
PPR	EFSA Panel on Plant Protection Products and their Residues
RIVM	RijksInstituut voor Volksgezondheid en Milieu, National Institute for Public Health and the Environment
RO	reverse osmosis
SOBEK	Suite of models for flood forecasting, optimisation of drainage systems, control of irrigation systems, sewer overflow design, river morphology, salt intrusion and surface water quality
STP	sewage treatment plant
TOP10	digital topographic map of the Netherlands
TOXSWA	TOXic substances in Surface Waters, model for simulating the fate and behaviour of organic chemicals in surface water and sediment
WG	working group
WUR	Wageningen University and Research
WUR-GH	WUR Greenhouse Horticulture

Appendix A. Threshold values for sodium in discharge water

The Directive greenhouse horticulture (Besluit Glastuinbouw 2002) gave limits for the sodium content in discharge water, dependent on the crop. Discharge was permitted when these limits were exceeded.

List 3 of Appendix 3 in the Directive Greenhouse Horticulture (Besluit Glastuinbouw 2002)

Crop	Sodium limit value (mmol/l)
tomato	8
sweet pepper	6
cucumber	6
aubergine (eggplant)	6
zucchini (courgette)	6
beans	6
lettuce	5
melon	6
strawberry	3
orchid	0
rose	4
carnation	4
gerbera	4
anthurium	3
amaryllis	4
lily	3
bouvardia	3
iris	3
others	5

Appendix B. DTG list

DTG stands for Definitielijst Toepassingsgebieden Gewasbeschermingsmiddelen. This is a list of areas of use of PPP, i.e. a crop or other application target. At Ctgb this list is used, amongst other things, to determine which environmental risk assessment methodology should be applied for the evaluation of a substance. In the GEM software (see Chapter 6), the list is used to select appropriate scenario settings (see main text) for the selected area of use. This appendix gives the crops that are known to be grown in greenhouses, and how they are handled in the software.

The DTG is a hierarchical system:
level 1. Sector, cultivation or application area
level 2. Crop group or equivalent
level 3. Crop subgroup or equivalent
level 4. Crop or equivalent

In general, an application is assessed at the crop level, unless all crops in a (sub)group are assessed in the same way. The software reflects this (see also Figure 6-2). The underlying database contains the necessary information for the calculations, e.g. the name of the reference crop and the number of plants per m^2.

Table B-1 DTG Level 1: sector, cultivation or application area. Relevant IDs for substrate cultivation are in bold.

ID	Area
1	arable crops
2	cultivated grassland
3	**fruit crops**
4	**vegetable crops**
5	**herb crops**
6	mushroom crops
7	**ornamental crops**
8	public green spaces
9	**forestry**
10	uncultivated land
11	watercourses
12	reed and osier crops
13	refuse heaps
14	in and around the house, private home environment
15	disinfectants

Table B-2 lists part of the parameterisation of soilless grown crops. For each of the crops, the scenario that is used for calculating the emissions is indicated (column REC). Furthermore, the table indicates how interception of PPP by the crop is parameterised: column RDC and following four columns.

Table B-2 Detailed information on crops and handling DTG items in GEM. Column 2: REC Reference Emission Crop 1) tomato, 2) ficus, 3) rose, 4) sweet pepper. Column 3: RDC Reference Deposition Crop (representative deposition crop), 1) cut flowers & pot plants, 2) lettuce & radish, 3) tomato & cucumber, 4) rose & gerbera, 5) young plants.

DTG item	REC	RDC	Type	Number of plants (m^{-2})	relative pot surface (m^2 m^{-2})	LAI at BBHC 33–97	Relative pot surface area based on literature or personal communication	Remarks
strawberry	4	2	soft fruit on substrate	2.5	0.025	4	estimated, based on average pot plant	cultivated on slabs, as well as in the soil, outside, in tunnels and GH
raspberry	4	1	shrub-like soft fruit on substrate	7	0.24	6	estimated (as ficus pot size 21 cm)	cultivated in pots, minor acreage
garden cress	3	5	young plants	750	0.2	1	estimated, based on tiny young plants like spathiphyllum (400/tray)	small crop but always on substrate, not only cress but also other germinating vegetables, e.g. Koppert cress
watercress	3	5	young plants	750	0.2	1	estimated, based on tiny young plants like spathiphyllum (400/tray)	small crop but always on substrate, not only cress but also other germinating vegetables
other vegetable sprouts	3	5	young plants	750	0.2	1	estimated, based on tiny young plants like spathiphyllum (400/tray)	small crop but always on substrate, not only cress but also other germinating vegetables, e.g. Koppert cress
courgette	1	3	fruit vegetables on substrate	1.3	0.013	4	Jan Janse, WUR-GH	zucchini, half of the acreage is on substrate, half grown in the soil
cucumbers	1	3	fruit vegetables on substrate	1.75	0.0175	4	Jan Janse, WUR-GH	conventional growth 100% substrate

DTG item	REC	RDC	Type	Number of plants (m^{-2})	relative pot surface (m^2 m^{-2})	LAI at BBHC 33–97	Relative pot surface area based on literature or personal communication	Remarks
aubergines	1	3	fruit vegetables on substrate	1.6	0.016	7	Jan Janse, WUR-GH	conventional growth 100% substrate
tomato	1	3	fruit vegetables on substrate	2.5	0.025	4	Jan Janse, WUR-GH	conventional growth 100% substrate
sweet pepper	4	3	fruit vegetables on substrate	2.3	0.023	7	Ruud van Maaswinkel, WUR-GH	conventional growth 100% substrate
basil	2	1	leafy vegetables on substrate	35	0.4	4	estimated, based on average pot plant (pot size 13 cm)	grown in GH as potting plant
chives	2	1	leafy vegetables on substrate	35	0.4	2	estimated, based on average pot plant (pot size 13 cm)	chive, grown in GH as potting plant
savoury	2	1	leafy vegetables on substrate	35	0.4	4	estimated, based on average pot plant (pot size 13 cm)	savoury, grown in GH as potting plant
lemon balm	2	1	leafy vegetables on substrate	35	0.4	4	estimated, based on average pot plant (pot size 13 cm)	lemon balm, grown in GH as potting plant
dill	2	1	leafy vegetables on substrate	35	0.4	4	estimated, based on average pot plant (pot size 13 cm)	dill, grown in GH as potting plant
tarragon	2	1	leafy vegetables on substrate	35	0.4	4	estimated, based on average pot plant (pot size 13 cm)	tarragon, grown in GH as potting plant
coriander	2	1	leafy vegetables on substrate	35	0.4	4	estimated, based on average pot plant (pot size 13 cm)	coriander, grown in GH as potting plant
parsley	2	1	leafy vegetables on substrate	35	0.4	4	estimated, based on average pot plant (pot size 13 cm)	parsley, grown in GH as potting plant
marjoram	2	1	leafy vegetables on substrate	35	0.4	4	estimated, based on average pot plant (pot size 13 cm)	marjoram, grown in GH as potting plant

DTG item	REC	RDC	Type	Number of plants (m^{-2})	relative pot surface (m^2 m^{-2})	LAI at BBHC 33–97	Relative pot surface area based on literature or personal communication	Remarks
oregano	2	1	leafy vegetables on substrate	35	0.4	4	estimated, based on average pot plant (pot size 13 cm)	oregano, grown in GH as potting plant
mint	2	1	leafy vegetables on substrate	35	0.4	4	estimated, based on average pot plant (pot size 13 cm)	mint, grown in GH as potting plant
rosemary	2	1	leafy vegetables on substrate	35	0.4	4	estimated, based on average pot plant (pot size 13 cm)	rosemary, grown in GH as potting plant
sage	2	1	leafy vegetables on substrate	35	0.4	4	estimated, based on average pot plant (pot size 13 cm)	sage, grown in GH as potting plant
thyme	2	1	leafy vegetables on substrate	35	0.4	4	estimated, based on average pot plant (pot size 13 cm)	thyme, grown in GH as potting plant
heartsease	2	1	perennials on substrate	35	0.4	3	estimated, based on average pot plant (pot size 13 cm)	viola tricolor, grown in GH as potting plant
winter bulb flower and corm flower forced cultivation	3	1	cut flowers on substrate	1000	0.96	0.5	estimated, based on bulb size 3.5 cm	"forcing" of common bulbflowers like tulip and hyacinth
summer bulb flower and corm flower forced cultivation	3	1	cut flowers on substrate	100	0.5	4	estimated, based on bulb size 8 cm	cultivation of lillium on peat and amaryllis (Hippestrum) on e.g. expanded clay
pot plants	2	1	pot plants, excluding orchids	26	0.68	5	average of several different pot plants	cultivation in containers in different substrates, except orchids
cut flowers	3	4	cut flowers on substrate	6	0.06	5	average of rose/ gerbera	cultivation on substrate

DTG item	REC	RDC	Type	Number of plants (m^{-2})	relative pot surface (m^2 m^{-2})	LAI at BBHC 33–97	Relative pot surface area based on literature or personal communication	Remarks
forced shrubs	3	1	cut flowers on substrate	6	0.6	5	estimated based on 40 cm container	cut hortensia, 'shrubs', e.g. syringae; cultivation in GH (at least partly) on containers
cut green	3	1	cut flowers on substrate	6	0.6	6	estimated based on 40 cm container	cultivation partly in containers
climbing plants	2	1	ornamentals on substrate in greenhouse	40	0.53	6	estimated as high pot plant-like dracaena (14 cm)	cultivation in GH or GH-like structures in containers, e.g. clematis
roses	2	1	ornamentals on substrate in greenhouse	26	0.68	5	average of several different pot plants	cultivation in GH or GH-like structures in containers, e.g. pot rose
conifers	2	1	ornamentals on substrate in greenhouse	7	0.24	6	estimated as ficus pot size 21 cm	cultivation in GH or GH-like structures in containers, e.g. thuja or cupressus
ornamental shrubs	2	1	ornamentals on substrate in greenhouse	7	0.24	6	estimated as ficus pot size 21 cm	cultivation in GH or GH-like structures in containers, e.g. acer, buddleia, hortensia, larger garden plants
heather	2	1	ornamentals on substrate in greenhouse	26	0.68	5	average of several different pot plants	cultivation in GH or GH-like structures in containers, e.g. calluna or erica

DTG item	REC	RDC	Type	Number of plants (m^{-2})	relative pot surface (m^2 m^{-2})	LAI at BBHC 33–97	Relative pot surface area based on literature or personal communication	Remarks
shelter belts, windbreaks and protective hedgerows	2	1	ornamentals on substrate in greenhouse	3	0.72	7	estimated (LAI as sweet pepper), grown in containers 120 x 20 cm	cultivation of hedera or fagus, on peat, grown on metal structures (e.g. mobilane)
lettuce	4	2	leafy vegetables on substrate	20	0.04	4	estimated, based on average pot plant	few growers on deep flow technique, mainly soil

Appendix C. Model A, PPP application by drip irrigation

This appendix gives the mathematical concepts of the behaviour of a substance in a soilless growing system, with PPP applied via the nutrient solution. The layout of the system is given in Figure C-1. The values in brackets are the assumed volumes of the tanks. The model is parameterised such that all values are rescaled to a greenhouse of 1 ha.

The PPP mass is applied in the mixing tank and is recirculated between the tanks, as shown in the figure, until it is discharged via the waste water tank as filter rinsing water or for sodium control to either surface water or a sewage system (note that in the scenario we consider all the discharged water to be discharged to surface water). An amount of 1.5% of the water used for crop cultivation is assumed to leach to groundwater.

C1. Water fluxes between tanks

Four water fluxes in the greenhouse are generated by the WATERSTREAMS model: crop evapotranspiration, filter discharge, discharge due to sodium control, and condensation water flux to the recirculation water. The other water fluxes between the tanks are calculated on the basis of water balances (most tanks have a constant volume) and some management conditions (e.g. the ratio between evapotranspiration and water supply to the crop).

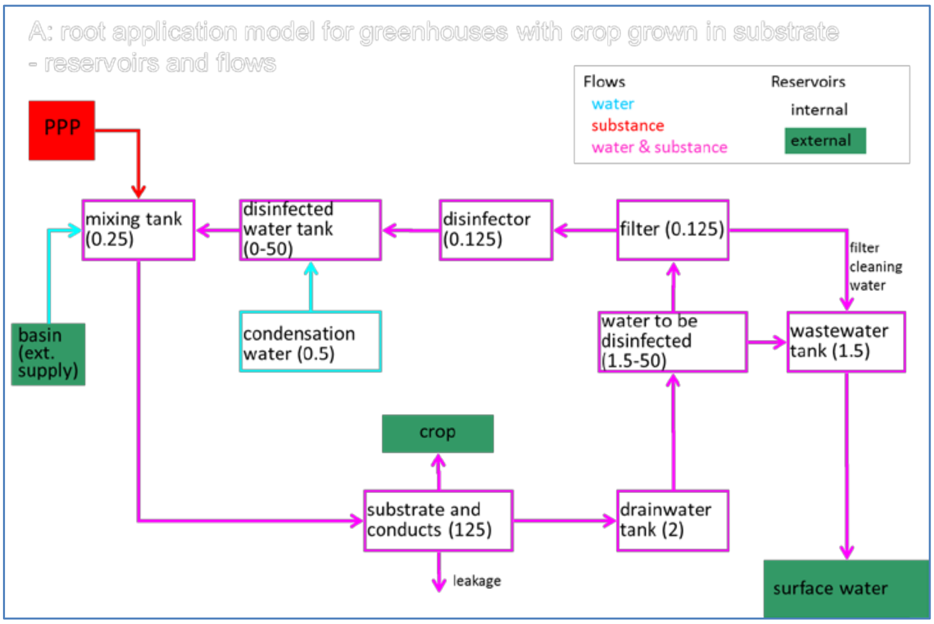

Figure C-1 Layout of the greenhouse model A, reservoir volumes (m^3) and substance flows scaled to 1 ha.

C2. The mass balance of a tank in the substrate model

In each tank in the substrate model instant mixing of the substance is assumed. The substrate model solves for each tank *i* (with a specified size) the conservation equation for the parent substance according to:

$$\frac{dm_i}{dt} = \sum_{j=1}^{n} q_{j,i} \frac{m_j}{v_j} - \sum_{k=1}^{m} q_{i,k} \frac{m_i}{v_i} - v_i R_{t,i} \quad (1)$$

and for the metabolites according to:

$$\frac{dm_i}{dt} = \sum_{j=1}^{n} q_{j,i} \frac{m_j}{v_j} - \sum_{k=1}^{m} q_{i,k} \frac{m_i}{v_i} - v_i R_{t,i} + v_i R_{f,i} \quad (2)$$

where

v_i volume of water in tank *i* (m)

m_i mass in tank *i* (kg)

$q_{i,j}$ flux from tank *i* to *j* (m^3 d^{-1})

$\sum_{j=1}^{n} q_{j,i} \frac{m_j}{v_j}$ sum of all incoming mass fluxes from the tanks *j* = 1,*n*, where *n* is the number of incoming water fluxes

$\sum_{k=1}^{m} q_{i,k} \frac{m_i}{v_i}$ sum of all the outgoing mass fluxes to the tanks *k* = 1,*m*, where *m* is the number of outgoing water fluxes.

$R_{t,i}$ is the transformation rate in tank i (kg m^{-3} d^{-1}), which is defined by (see also Leistra et al. 2001, eq 7.1):

$$R_{t,i} = k_t \frac{m_i}{v_i} \quad (3)$$

where

k_t rate coefficient for transformation (d^{-1})

$R_{f,i}$ formation rate of a metabolite (e.g. product 1) in tank *i*, defined by (see Leistra et al. 2001, eq. 7.2):

$$R_{f,i,1} = \chi_{p,1} \frac{M_1}{M_p} R_{t,i,p} \quad (4)$$

where

$R_{f,i,1}$ rate of formation of product 1 from the parent compound in tank *i* (kg m^{-3} d^{-1})

$\chi_{p,1}$ molar fraction of parent transformed to product 1

M_1 molar mass of product 1 (kg mol^{-1})

M_p molar mass of parent (kg mol^{-1})

$R_{t,I,p}$ the overall rate of transformation of the parent compound in tank *i* (kg m^{-3} d^{-1}).

Plant uptake is based on Briggs et al. (1982), the transpiration stream concentration factor being a function of the octanol water partitioning coefficient.

C3. Finite difference approximation
Using the explicit Euler numerical scheme, the ordinary differential equation (2) can be approximated by:

$$m_i^{t+1} = m_i^t + \left(\sum_{j=1}^{n} q_{j,i}^{t+1} \frac{m_j^t}{v_j^t} - \sum_{k=1}^{m} q_{i,k}^{t+1} \frac{m_i^t}{v_j^t} - k_i m_i^t + v_i^t R_{f,i}^t \right) \Delta t \qquad (5)$$

C4. Error mass balance
The mass balance error is calculated using the following relationship for each compound at a given time *t**:

$$E(m_{sys}) = -\sum_{j=1}^{n} m_j^{t^*} + \sum_{j=1}^{n} (\int_{t=0}^{t^*} J_{appl}^t dt) - \int_{t=0}^{t^*} J_{ext} dt + \sum_{j=1}^{n} (\int_{t=0}^{t^*} v_j R_{f,j} dt) - \sum_{j=1}^{n} (\int_{t=0}^{t^*} v_j R_{t,j} dt) \qquad (6)$$

where

$E(m_{sys})$	total error in mass in the system (kg)
m_j	mass in tank *j* at $t=t^*$ (kg)
$J_{appl}\ (t)$	applied mass rate to a specific tank *j* at *t* (kg d^{-1})
$J_{ext}\ (t)$	mass rate that flows out of the greenhouse to the external reservoirs at *t* (kg d^{-1}).

The simulation uses a constant time step of 1 min.

Appendix D. Model B, PPP spray application to crops grown on shielded slabs

D1. Background

In model B the PPP is applied via spraying, fogging or fumigation: the substance is applied to the crop canopy, but may also reach the greenhouse floor or stay airborne in the greenhouse air. The root compartment is shielded against direct exposure. PPP may enter the water-nutrient solution that is recycled within the greenhouse only via condensation water that flows from the glass surface area, the sidewalls and the roofs into the clean water tank. See also Figure D-2 below: the processes and interactions are added to the substrate model A, as discussed in Appendix C.

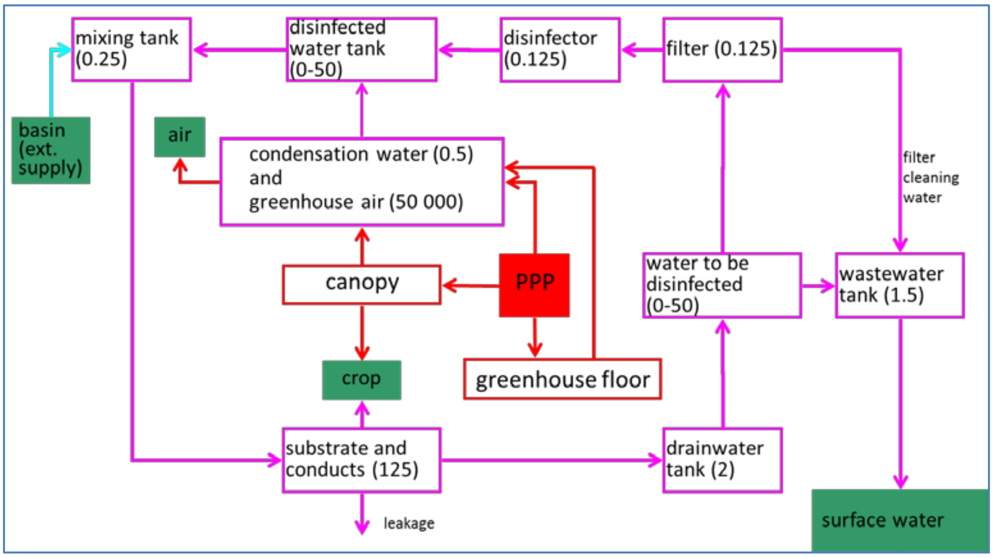

Figure D-2 Layout of the greenhouse model B, reservoir volumes (m^3) and substance flows scaled to 1 ha.

D2. Plant Protection Product application

During spraying, fogging or fumigation the PPP is distributed between the plant leaves, the greenhouse floor and the greenhouse air:

$$A_{a,gr} = A_{a,p} + A_{a,a} + A_{a,f} \quad (1)$$

where

$A_{a,gr}$ areic mass applied in the greenhouse (kg m^{-2})
$A_{a,p}$ areic mass applied deposited on the plants (kg m^{-2})
$A_{a,a}$ areic mass that stays in the greenhouse air (kg m^{-2})
$A_{a,f}$ the areic mass deposited on the greenhouse floor (kg m^{-2}).

The initial distribution (just after application) over the crop foliage, the greenhouse air and condensation water, and the greenhouse floor is estimated according to:

$$A_{a,p} = f_{a,p}A_{a,gr}$$
$$A_{a,f} = (1 - f_{a,p} - f_{a,a})A_{a,gr} \quad (2)$$
$$A_{a,a} = f_{a,a}A_{a,gr}$$

where

$f_{a,p}$ fraction of the total areic mass applied to the plants (-)

$f_{a,a}$ fraction of the total areic mass applied that is volatilised into the greenhouse air (-).

$f_{a,p}$ and $f_{a,a}$ depend on the application type and the growth stage of the crop. Since no detailed information is available on the relationship between application type, growth stage and $f_{a,p}$ and $f_{a,a}$, these are assumed constant; the value depends on the crop type and the application based on expert opinion (See Appendix B).

D3. Mass balance equations

Four new entities to solve the mass balance are introduced as compared with model A: foliage, greenhouse floor, condensation water and greenhouse air.

D3.1 Foliage

The PPP on the crop foliage is subject to transformation, volatilisation and deposition on the plant leaves. Wash-off and the formation and degradation of metabolites are not considered.

The conservation equation for areic mass on plants reads:

$$\frac{dA_p}{dt} = (J_{d,p} - J_{v,p}) - k_pA_p + A_{a,p} \quad (3)$$

where

A_p mass of PPP on the plant (kg m^{-2})

k_p rate coefficient for dissipation (lumped processes: penetration and transformation) of PPP on the crop canopy (d^{-1}), independent of temperature. The default value for the half-life on crop foliage is 10 d. Wash-off is not considered.

$J_{d,p}$ is the deposition rate on the plant (kg m^{-2} d^{-1}), defined by:

$$J_{d,p} = \text{LAI}\,\frac{c_a - c_p}{r_a} \text{ when } c_p < c_a \quad (4)$$

$J_{v,p}$ is the volatilisation rate from the foliage of the plant (kg m^{-2} d^{-1}), defined by:

$$J_{v,p} = \frac{A_p}{A_{ref}}\frac{c_p - c_a}{r_a} \text{ when } c_p > c_a \quad (5)$$

where

A_p areic mass on the plant (kg m^{-2})

A_{ref} reference mass, which is 1.10^{-4} kg m^{-2}

c_p concentration in the gas phase at the canopy (kg m^{-2})

c_a concentration in the greenhouse air (kg m^{-3})

r_a laminar boundary layer resistance, 1.16 10^{-3} d m^{-1} (Jacobs et al. 2007).
LAI Leaf Area Index of the crop (m^2 m^{-2}). The LAI is assumed to be 5, independent of the greenhouse model crop or development stage.

The concentration in the gas phase at the canopy is calculated according the general gas law:

$$c_p = \frac{M\, P_{act}}{R\, T_{gh}} \quad (6)$$

where
P_{act} actual saturated vapour pressure (Pa)
M molar mass of the PPP (kg mol^{-1})
R molar gas constant (8.314 J mol^{-1} K^{-1})
T_{gh} temperature in greenhouse, assumed to be 293.15 K (20 °C)

The actual saturated vapour pressure is calculated by the Clausius Clapeyron equation:

$$P_{act} = P_{ref} \exp\left(\frac{-H_v}{R}\left(T_{gh}^{-1} - T_{ref}^{-1}\right)\right) \quad (7)$$

where
P_{ref} reference saturated vapour pressure of the substance (Pa)
T_{ref} reference temperature (K), being 293.15 K
H_v molar enthalpy of vaporisation (J mol^{-1}), being 96000 J mol^{-1}.

D3.2 Greenhouse floor
PPP on the greenhouse floor is subject to transformation and volatilisation. PPP may also be deposited from the air on the greenhouse floor. The formation and degradation of metabolites is not considered.

The conservation equation for areic mass on the greenhouse floor reads:

$$\frac{dA_f}{dt} = \left(J_{d,f} - J_{v,f}\right) - k_f A_f + A_{a,f} \quad (8)$$

where
A_f mass of PPP on the greenhouse floor (kg m^{-2})
k_f rate coefficient for dissipation (d^{-1}). k_f is treated like k_p and is not temperature-dependent. The suggested value for the half-life on the greenhouse floor is 100 d.
$J_{d,f}$ the deposition rate on the greenhouse floor (kg m^{-2} d^{-1}), defined by:

$$J_{d,f} = \text{LAI}\, \frac{c_a - c_f}{r_a} \text{ when } c_f < c_a \quad (9)$$

$J_{v,f}$ is the volatilisation rate from the greenhouse floor (kg m^{-2} d^{-1}):

$$J_{v,f} = \frac{A_f}{A_{ref}} \frac{c_f - c_a}{r_a} \text{ when } c_f > c_a \quad (10)$$

where

A_f areic mass of the greenhouse floor (kg m^{-2})

A_{ref} reference mass (kg m^{-2}), which is 1.10-4 kg m^{-2}

c_f concentration in the gas phase at the greenhouse floor (kg m^{-2})

c_a concentration in the greenhouse air (kg m^{-3})

r_a laminar boundary layer resistance (d m^{-1}), being 1.16 10^{-3} d m^{-1} (Jacobs et al. 2007).

The concentration in the gas phase at the greenhouse floor is calculated similar to the crop canopy, using Eq. (6) and (7).

D3.3 Greenhouse air and condensation water

PPP concentrations in greenhouse air are subject to degradation and exchange processes with the crop canopy and the greenhouse floor (i.e. deposition and volatilisation). The formation and degradation of metabolites is not considered. The greenhouse air is in equilibrium with the condensation water in the greenhouse. The applied volume of air in a greenhouse of 1 ha is 50,000 m^3 and the volume of condensation water is 0.53 m^3. Emission of PPP to (outside) air may occur due to ventilation.

The conservation equation for greenhouse air including condensation water reads:

$$\frac{dA_{a+w}}{dt} = J_{v,p} + J_{v,f} - J_{d,p} - J_{d,f} - J_{vent} - J_{circ} - k_a A_a - k_c A_c + A_{a,a} \quad (11)$$

where

A_{a+w} areic mass in the greenhouse air and condensation water (kg m^{-2})

$J_{v,p}$ areic mass rate of volatilisation from the plant (kg m^{-2} d^{-1})

$J_{v,f}$ areic mass rate of volatilisation from the greenhouse floor (kg m^{-2} d^{-1})

$J_{d,p}$ areic mass rate of deposition on the plant canopy (kg m^{-2} d^{-1})

$J_{d,f}$ areic mass rate of deposition on the greenhouse floor (kg m^{-2} d^{-1})

J_{vent} areic mass flux emitted to air due to ventilation (kg m^{-2} d^{-1});

J_{circ} areic mass flux emitted into the recirculation water (kg m^{-2} d^{-1})

A_a areic mass in the greenhouse air only (kg m^{-2})

A_c areic mass in the condensation water only (kg m^{-2})

k_a rate coefficient for transformation in greenhouse air (d^{-1})

k_c rate coefficient for transformation in water (d^{-1}).

The rate coefficients of transformation are temperature-dependent; the temperature effect is calculated using the Arrhenius equation. The half-life in the condensation water is considered to be equal to the half-life in the tanks. $J_{v,p}$, $J_{d,p}$, $J_{v,f}$ and $J_{d,f}$ are calculated using Eq. (4), (5), (8) and (9), respectively.

The partitioning of the PPP between the gas phase and the condensation water is described by the Henry coefficient:

$$K_H = \frac{c_a}{c_w} \quad (12)$$

The concentration in the gas phase, c_a (kg m^{-3}), is calculated using the general gas law (see Eq. (6)). The concentration in condensation water is assumed to be equal to the PPP solubility in water, S (kg m^{-3}). Both the solubility and the vapour pressure, P_{act}, are temperature-dependent. For the vapour pressure the temperature dependency is given the Clausius Clayperon (Eq. (7)). A similar equation is used for the effect of temperature on substance solubility in water:

$$S = S_r exp\left(\frac{-\Delta H_d}{R}\left(T_{gh}^{-1} - T_{ref}^{-1}\right)\right) \quad (13)$$

where
S solubility in water (kg m^{-3})
S_r solubility at reference temperature (kg m^{-3})
ΔH_d molar enthalpy of dissolution in water, which is 27000 J mol^{-1}.

The areic mass in the air-condensation water-system is given by:

$$A_{a+w} = V_a c_a + V_c c_w \quad (14)$$

where
V_a (areic) air volume; value used in calculation is 5 m^3 m^{-2}
V_c (areic) condensation water volume; value used in calculation is 0.53 10^{-4} m^3 m^{-2}.

Eq. (14) can be rewritten using the Henry coefficient:

$$c_a = \frac{A_{a+w}}{V_a + {V_c}/{K_H}} \text{ and } A_a = V_a c_a \quad (15)$$

$$c_w = \frac{A_{a+w}}{V_a K_H + V_c} \text{ and } A_w = V_c c_w \quad (16)$$

Emission of PPP towards air occurs through transport with the ventilated greenhouse air. The daily emitted mass of PPP via the greenhouse air towards the air outside, J_{vent} (kg m^{-2} d^{-1}), depends on the air exchange rate coefficient, N_{vent} (d^{-1}), of the greenhouse and c_a:

$$J_{vent} = n_{vent} V_a c_a \quad (17)$$

n_{vent} is estimated to be 50 d^{-1}.

D4. Implementation into the model

The Euler numerical scheme is used to solve the ordinary differential equations.

Appendix E. Model C, PPP spray application to crop grown in pots in an ebb/flow system

E1. Background

In model C the PPP is applied via spraying, fogging or fumigation. The substance is applied to the crop canopy but exposure of the root compartment is possible. The system is applicable to the cultivation of pot plants where the individual pots are not covered with plastic. The PPP is applied to the plant leaves, the substrate and water on the tables. The areal fraction covered with pots is f_{pot}.

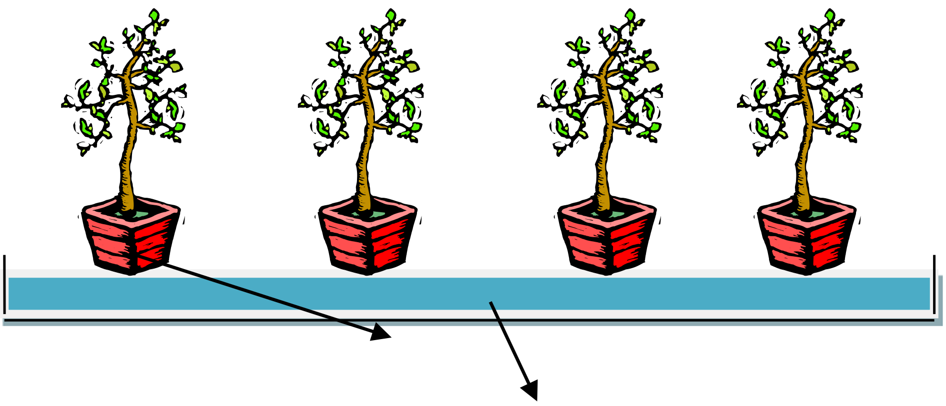

Figure E-1 Cultivation of pot plants.

The water flow system is similar to the flow system of models A and B. The system differs from model B (the shielded roots system) in that direct deposition on the recirculation water on the tables forms an additional source of PPP that may be emitted to the surface water. In the conceptual model the recirculation water on the tables is referred to as cultivation water (total volume estimated 125 m^3).

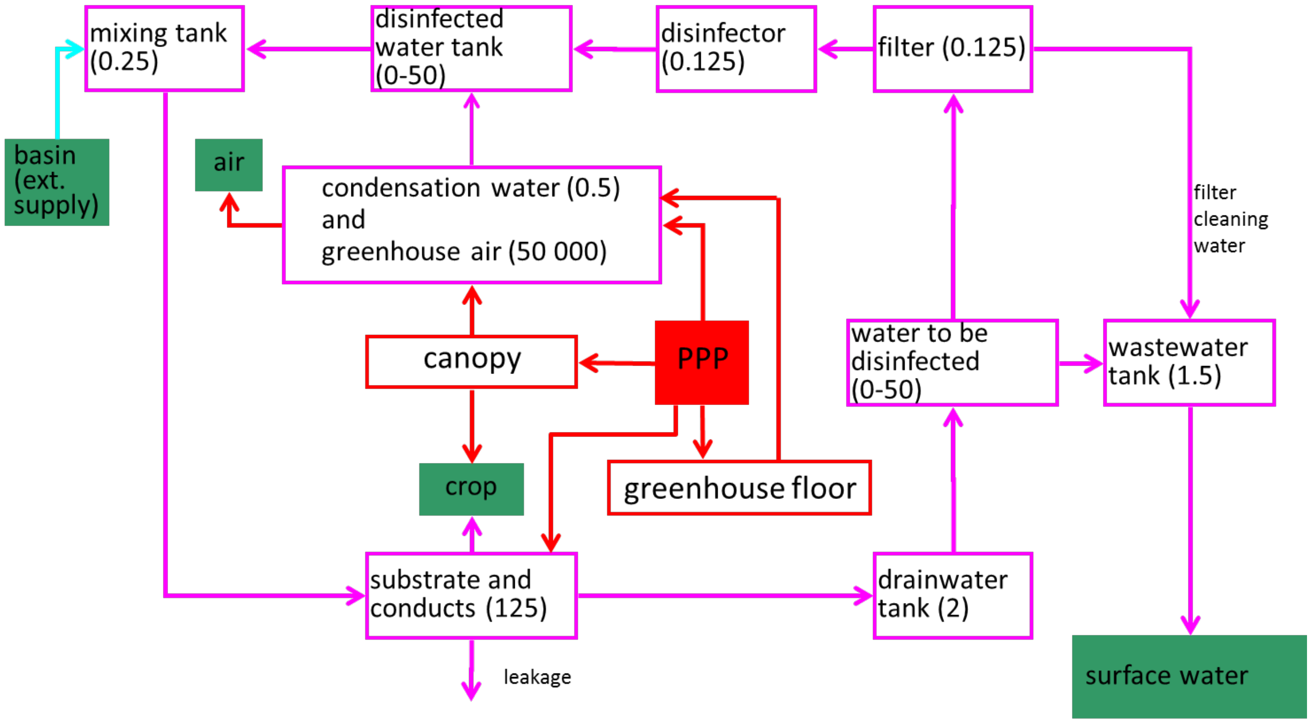

Figure E-2 Layout of the greenhouse model C, reservoir volumes (m^3) and substance flows scaled to 1 ha.

E2. PPP application

During spraying, fogging or fumigation the PPP is distributed between the plant leaves, the substrate, the recirculation water and the greenhouse air:

$$A_{a,gr} = A_{a,p} + A_{a,a} + A_{a,sub} + A_{a,cult} \quad (1)$$

where

$A_{a,gr}$ areic mass applied in the greenhouse (kg m^{-2})
$A_{a,p}$ areic mass applied on the plants (kg m^{-2})
$A_{a,a}$ areic mass initially volatilised into the greenhouse air (kg m^{-2})
$A_{a,sub}$ areic mass applied on substrate (in the pots) (kg m^{-2})
$A_{a,cult}$ areic mass applied in the recirculation water (kg m^{-2}) (referred to as the cultivation tank). The greenhouse is assumed to cover 1 ha and the application is assumed to take place over two hours.

The initial distribution over the crop foliage, the greenhouse air and condensation water, the substrate and the recirculation water is estimated according to:

$$\begin{aligned} A_{a,p} &= f_{a,p} A_{a,gr} \\ A_{a,a} &= f_{a,a} A_{a,gr} \\ A_{a,sub} &= (1 - f_{a,p} - f_{a,a}) f_{pot} A_{a,gr} \\ A_{a,cult} &= (1 - f_{a,p} - f_{a,a})(1 - f_{pot}) A_{a,gr} \end{aligned} \quad (2)$$

Similar to model B

$f_{a,p}$ fraction of the total areic mass initially applied to the plants (-)

$f_{a,a}$ fraction of the total areic mass initially applied that is volatilised into the greenhouse air (-)

f_{pot} fraction of the surface covered with pots (-)

$f_{a,p}$ and $f_{a,a}$ depend on the application type and the growth stage of the crop. Since no detailed information is available on the relationship between application type, growth stage and $f_{a,p}$ and $f_{a,a}$, these are constants, the values depending on the crop type and the application being based on expert judgement (see Appendix B).

Continuous exchange of PPP occurs between resp. the crop foliage, the substrate, the recirculation water and the greenhouse air. This exchange depends on the concentration gradients between the greenhouse air and the concentration directly above or within the foliage, substrate and recirculation water.

E3. Mass balance equations

E3.1 Foliage

The PPP on the crop foliage is subject to dissipation/transformation, volatilisation from and deposition on the plant leaves. Wash-off is not considered because water to the plants is supplied via the tables, not by overhead sprinkling/irrigation.

The conservation equation for areic mass on plants reads:

$$\frac{dA_p}{dt} = \left(J_{d,p} - J_{v,p}\right) - k_p A_p + A_{a,p} \qquad (3)$$

where

A_p mass of PPP on the plant per m^2 greenhouse (kg m^{-2})

k_p rate coefficient for dissipation (d^{-1}) (lumped process: penetration and transformation) of pesticide on the plant leaves, independent of temperature. The default value for the half-life on crop foliage is 10 d.

$J_{d,p}$ is the deposition rate on the plant (kg m^{-2} d^{-1}), defined by:

$$J_{d,p} = LAI\ D_a \frac{c_a - c_p}{d_{lam}} \qquad \text{when } c_p < c_a \qquad (4)$$

where

d_{lam} equivalent thickness of the laminar air boundary layer (m). d_{lam} depends on the plant type and may vary between 0.5 and 1 mm; the value used in the calculations is 0.5 mm.

$J_{v,p}$ is the volatilisation rate from the foliage of the plant (kg m^{-2} d^{-1}):

$$J_{v,p} = \mathrm{LAI}\ f_{mass} D_a \frac{c_p - c_a}{d_{lam}} \qquad \text{when } c_p > c_a \qquad (5)$$

where

$$f_{mass} = \frac{A_{leaves}}{A_{ref}} \quad (6)$$

A_{leaves} areic mass on the plant per m^2 of leaves (kg m^{-2})
A_{ref} reference areic mass (kg m^{-2}), which is 1.10-4 kg m^{-2}
c_p concentration in the gas phase at the canopy (kg m^{-3})
c_a concentration in the greenhouse air (kg m^{-3})
LAI Leaf Area Index of the crop (m^2 m^{-2}). The LAI differs per greenhouse crop and development stage (see Appendix C).
D_a diffusion coefficient of in air (m^2 d^{-1})

The concentration in the gas phase at the canopy is calculated according the General Gas Law:

$$c_p = \frac{M\, P_{act}}{R\, T_{gh}} \quad (7)$$

where
P_{act} actual saturated vapour pressure (Pa)
M molar mass of the PPP (kg mol^{-1})
R molar gas constant (8.314 J mol^{-1} K^{-1})
T_{gh} temperature in greenhouse (K).

The actual saturated vapour pressure is calculated by the Clausius Clapeyron equation:

$$P_{act} = P_{ref} \exp\left(\frac{-H_v}{R}\left(T_{gh}^{-1} - T_{ref}^{-1}\right)\right) \quad (8)$$

where
P_{ref} reference saturated vapour pressure of the pesticide (Pa)
T_{ref} reference temperature (K), being 293.15 K
H_v molar enthalpy of vaporisation (J mol^{-1}), being 96000 J mol^{-1}.

E3.2 Substrate in the pots

It is assumed that the PPP deposited on pot substrate is subject to transformation, diffusion, volatilisation and deposition. Only the upper layer of the substrate is considered to interact with the greenhouse air (see Figure E-3). From this upper layer the pesticide diffuses downwards. This is considered to be a sink term, i.e. the diffused PPP is considered to be unavailable for interaction with greenhouse air. The formation and degradation of metabolites is not considered. After application, the PPP partitions between the water phase, the solid phase and the gas phase within the substrate. It is assumed that there is no exchange between the substrate and the recirculation water on the tables.

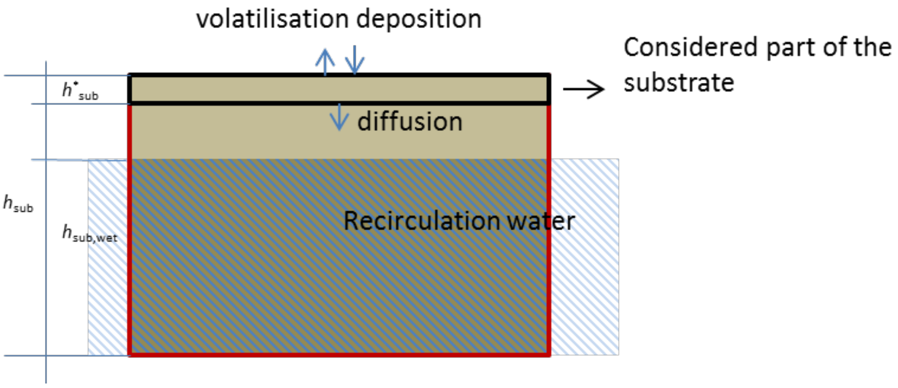

Figure E-3 Substrate processes and interaction with greenhouse air.

The pot height is taken to be 15 cm. The wetted part of the substrate ($h_{sub,wet}$) is assumed to be 10 cm. The height of the part that interacts with greenhouse air (h^*_{sub}) is assumed to be 2 mm (grain size; e.g. Millington and Quirk 1960). The dry bulk density of the substrate is 1,000 kg m^{-3} and the porosity, θ, is 0.6. The fraction of water, $f_{w,sub}$, in the upper 5 cm is assumed to be 0.1 of the pore volume.

The conservation equation for areic mass on the substrate reads:

$$\frac{dA_{sub}}{dt} = \left(J_{d,sub} - J_{v,sub} - J_{diff,sub}\right) - k_{sub}A_{sub} + A_{a,sub} \qquad (9)$$

where

A_{sub} mass of pesticide on substrate (kg m^{-2})

k_{sub} rate coefficient for dissipation of pesticide (lumped processes) (d^{-1}). k_{sub} is temperature-dependent.

$J_{d,sub}$ deposition rate on substrate (kg m^{-2} d^{-1}), defined by (see also Leistra 2005):

$$J_{d,sub} = f_{pot} D_a \frac{c_a - c_{g,sub}}{d_{lam}} \qquad \text{when } c_{sub} < c_a \qquad (10)$$

$J_{v,sub}$ volatilisation rate from the greenhouse floor (kg m^{-2} d^{-1}):

$$J_{v,sub} = f_{pot} D_a \frac{c_{g,sub} - c_a}{d_{lam}} \qquad \text{when } c_{sub} > c_a \qquad (11)$$

where

$c_{g,sub}$ concentration in the gas phase at the greenhouse floor (kg m^{-3})

c_a concentration in the greenhouse air (kg m^{-3})

D_a the diffusion coefficient of pesticide air (m^2 d^{-1})

d_{lam} equivalent thickness of the laminar air boundary layer (m). d_{lam} depends on the plant type and may vary between 0.5 and 1 mm; the value used in the calculations is 0.5 mm.

$J_{diff,sub}$ diffusive downward flux (kg m^{-2} d^{-1}). Assuming that the concentration below the considered layer approximates to zero, the flux can be derived as:

$$J_{diff,sub} = f_{pot} D_{a,sub} \frac{c_{g,sub}}{h^*_{sub}} \quad (12)$$

where the diffusion coefficient in substrate ($D_{a,sub}$) is calculated from D_a (Millington and Quirk 1960):

$$D_{a,sub} = \theta^{1/3} D_a \quad (13)$$

The concentration in the gas phase of the substrate, $c_{g,sub}$, is calculated assuming instantaneous partitioning between the solid, liquid and gas phase within the substrate:

$$c_{sub} = \varepsilon_g c_{g,sub} + \varepsilon_l c_{l,sub} + \rho_s X \quad (14)$$

where

ε_g volume fraction of the gas phase (m^3 m^{-3})
X adsorbed pesticide content (kg kg^{-1})
ρ_s dry substrate bulk density (kg m^{-3}), assumed to be 1000 kg m^{-3}.

Rewriting Eq. (12) using

$$c_{sub} = {A_{sub}}/{h^*_{sub}}$$

$$\varepsilon_l = f_{w,sub}\theta$$

$$\varepsilon_g = (1 - f_{w,sub})\theta$$

$$X = K_{OM} m_{OM} c_l \quad \text{and}$$

$$c_l = {c_g}/{K_H}$$

gives:

$$c_{g,sub} = \frac{A_{sub}}{\left((1 - f_{w,sub})\theta + f_{w,sub}\theta/K_H + \rho_s K_{OM} m_{OM}/K_H\right) h^*_{sub}} \quad (16)$$

where

$f_{w,sub}$ fraction of water in the pores of the upper layer of substrate (-)
K_{OM} equilibrium sorption coefficient on soil organic matter (m^3 kg^{-1})
K_H Henry coefficient (-)
m_{OM} mass fraction organic matter in the substrate (kg kg^{-1}), set to 0.1 kg kg^{-1}.

E3.3 Recirculation water on the tables

The fraction of applied pesticide that was deposited on the recirculation water is assigned to the cultivation reservoir/tank. The pesticide in the cultivation tank is subject to transformation, sorption, deposition and volatilisation. Also metabolite formation and degradation is considered. The conservation equation for the recirculation water is solved using the general tank conservation equation. However, one term is added on the right hand side of the equation:

$$\frac{dm_{cult}}{dt} = \sum_{j=1}^{1} q_{j,cult}\frac{m_j}{v_j} - \sum_{k=1}^{3} q_{cult,k}c_{cult} - v_{cult}R_{t,cult} + v_{cult}R_{f,cult} + \left(J_{d,cult} - J_{v,cult}\right)S_{gh} \tag{17}$$

where

v_i volume of water in tank i (m^3)

m_i total mass in tank i (kg)

c_{cult} concentration in the water phase in the cultivation tank (kg m^{-3})

$q_{i,j}$ water flux from tank i to j (m^3 d^{-1}).

First term RHS is the incoming mass flux from the tanks j = 1 (mixing tank). Second term RHS is the sum of all the outgoing mass fluxes, being the leakage fraction (k=1) and the water flux to the plant (k=2) and to the drainage tank (k=3).

$R_{t,cult}$ transformation rate (kg m^{-3} d^{-1}) in water in the cultivation tank

$R_{f,cult}$ formation rate of a metabolite (e.g. product 1) in water in the cultivation tank

S_{gh} greenhouse area (m^2), i.e. 10,000 m^2

$J_{d,cult}$ deposition rate (kg m^{-2} d^{-1}) on the recirculation water in the cultivation tank (on the tables), defined by:

$$J_{d,cult} = \left(1 - f_{pot}\right)D_a\frac{c_a - c_{g,cult}}{d_{lam}} \qquad \text{when } c_{g,cult} < c_a \tag{18}$$

$J_{v,cult}$ volatilisation rate (kg m^{-2} d^{-1}) from the tables/cultivation tank, defined by:

$$J_{v,cult} = \left(1 - f_{pot}\right)D_a\frac{c_{g,cult} - c_a}{d_{lam}} \qquad \text{when } c_{g,cult} > c_a \tag{19}$$

where

$c_{g,cult}$ concentration in the gas phase at the greenhouse floor (kg m^{-2})

c_a concentration in the greenhouse air (kg m^{-3}).

The concentration in the gas phase above the tables, $c_{g,cult}$, is calculated using Henry's law and assuming partitioning between the solid and the liquid phases:

$$c_{g,cult} = K_H \frac{m_{cult}}{V_{cult} + S_{gh} h_{sub,wet} f_{pot} \rho_s K_{OM} m_{OM}} \tag{20}$$

Note that here only the wetted part of the organic matter in the substrate is involved in the sorption of pesticides.

E3.4 Greenhouse air and condensation water

Pesticide concentrations in greenhouse air are subject to degradation and exchange processes with the crop canopy and the greenhouse floor (i.e. deposition and volatilisation). The formation and degradation of metabolites is not considered. The greenhouse air is in equilibrium with the condensation water in the greenhouse. The volume of air in a greenhouse of 1 ha is 50,000 m^3 in the calculations and the volume of condensation water is 0.53 m^3. This volume is considered to be constant over time. The emission to the recirculation water via the condensation water flux is time-dependent, i.e. it depends on the water fluxes provided by the WATERSTREAMS model. The emission of pesticide to (outside) air may occur due to ventilation.

The conservation equation for greenhouse air including condensation water is given by:

$$\frac{dA_{a+w}}{dt} = J_{v,p} + J_{v,sub} + J_{v,cult} - J_{d,p} - J_{d,sub} - J_{d,cult} - J_{vent} - J_{circ} - k_a A_a - k_c A_c + A_{a,a} \tag{21}$$

where

A_{a+w} areic mass in greenhouse air and condensation water (kg m^{-2})
$J_{v,p}$ areic mass rate of volatilisation from the plant (kg m^{-2} d^{-1})
$J_{v,sub}$ areic mass rate of volatilisation from the substrate (kg m^{-2} d^{-1})
$J_{v,cult}$ areic mass rate of volatilisation from recirculation water (i.e. cultivation tank) (kg m^{-2} d^{-1})
$J_{d,p}$ areic mass rate of deposition on the plant canopy (kg m^{-2} d^{-1})
$J_{d,sub}$ areic mass rate of deposition on the substrate (kg m^{-2} d^{-1})
$J_{d,cult}$ areic mass rate of deposition on the recirculation water (i.e. cultivation tank) (kg m^{-2} d^{-1})
J_{vent} areic mass flux emitted to air due to ventilation (kg m^{-2} d^{-1})
J_{circ} areic mass flux emitted into the recirculation water via the condensation water flux (kg m^{-2} d^{-1})
A_a areic mass in the greenhouse air only (kg m^{-2})
A_c areic mass in the condensation water only (kg m^{-2})
k_a rate coefficient for transformation in greenhouse air (d^{-1})
k_c rate coefficient for transformation in water (d^{-1}).

The rate coefficients of transformation are temperature-dependent; the temperature effect is calculated using the Arrhenius equation. $J_{v,p}$, $J_{d,p}$, $J_{v,sub}$, $J_{d,sub}$, $J_{v,cult}$ and $J_{d,cult}$ are calculated using Eq. (4), (5), (10), (11), (18) and (19), respectively.

The concentration in the gas phase, c_a (kg m^{-3}), is calculated using the General Gas Law (see Eq. (7)). The pesticide concentration in condensation water is assumed to be equal to the pesticide solubility in water, S (kg m^{-3}). Both the solubility and the vapour pressure, Pact, are temperature-dependent. For the vapour pressure the temperature dependency is given by the Clausius Clayperon Eq. (8). A similar equation is used for the effect of temperature on pesticide solubility in water:

$$S = S_r exp\left(\frac{-\Delta H_d}{R}\left(T_{gh}^{-1} - T_{ref}^{-1}\right)\right) \quad (22)$$

where
S pesticide solubility in water (kg m^{-3})
S_r pesticide solubility at reference temperature (kg m^{-3})
ΔH_d molar enthalpy of dissolution in water (J mol^{-1}); suggested value is 27,000 J mol^{-1}.

Given equilibrium between the gas phase and the liquid phase, the areic mass in the air condensation water system is given by:

$$A_{a+w} = V_a c_a + V_c c_w \quad (23)$$

where
V_a (areic) air volume (m^3 m^{-2}); in the scenario calculations 5 m^3 m^{-2} is used
V_c (areic) condensation water volume (m^3 m^{-2}); a volume of 0.53 10^{-4} m^3 m^{-2} is used in the scenario calculations.

Eq. (23) can be rewritten using the Henry coefficient:

$$c_a = \frac{A_{a+w}}{V_a + {V_c^*}/{K_H}} \quad \text{and} \quad A_a = V_a c_a \quad (24)$$

$$c_w = \frac{A_{a+w}}{V_a K_H + V_c^*} \quad \text{and} \quad A_w = V_c c_w \quad (25)$$

To account for the partitioning between air and water being a transient process, a reduction factor has been introduced of 0.1. Hence,

$$c_w^* = 0.1 c_w \quad (26)$$

The emission of PPP towards air occurs through transport with the ventilated greenhouse air. The daily mass of pesticide emitted via the greenhouse air towards the outside air, J_{vent} (kg m^{-2} d^{-1}), depends on the air exchange rate coefficient, n_{vent} (d^{-1}), of the greenhouse and c_a:

$$J_{vent} = n_{vent} V_a c_a \quad (27)$$

n_{vent} is estimated to be 50 d^{-1}.

RIVM

De zorg voor morgen begint vandaag