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RESEARCH

Development of an aquatic exposure assessment model for Imidacloprid in sewage treatment plant discharges arising from use of veterinary medicinal products

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Abstract

Background: Imidacloprid is an active ingredient included in plant protection, biocidal and veterinary medicinal products (VMPs). VMPs containing Imidacloprid are formulated as spot-on products or collars and designed to protect pets, predominantly dogs and cats, from parasite infestation. Monitoring data collected under the Water Framework Directive between 2016 and 2018 showed detectable and varying levels of Imidacloprid in the UK surface water bodies. The aim of the work was to investigate the potential contribution of VMPs by developing a model for predicting the emissions from sewage treatment plants from the use of dog and cat spot-on and collar VMPs. Due to the absence of appropriate exposure models for VMPs, the model was built based on the principles of environmental exposure assessment for biocidal products.

Results: Three emission paths were considered to be the most likely routes for repeated emissions to waterways from the use of spot-on and collar VMPs, i.e., transfer to pet bedding followed by washing, washing/bathing of dogs, and walking dogs in the rain. The developed model was used to calculate the Imidacloprid concentrations in surface water after discharge from wastewater treatment plants. Realistic worst-case input parameters were deduced from sales and survey data and experimental studies. Modelled total concentrations in surface water for each pathway ranged from 0.84 to 4.8 ng/L. The calculated concentrations did not exceed the ecological thresholds for the most sensitive aquatic invertebrate organisms and were found to be much lower than the UK monitoring data for river water. For example, the calculated concentration from the bathing/washing of dogs was < 3% of the highest levels of Imidacloprid measured in surface waters.

Conclusion: In conclusion, a model has been successfully built and applied. The modelled data indicate that these VMPs make only a very small contribution to the levels of Imidacloprid observed in the UK water monitoring programme. Further, calculated concentrations do not exceed ecotoxicological threshold values indicating acceptable chronic safety to aquatic organisms.

Keywords: Imidacloprid, Veterinary medicinal product, Surface water, Scenarios, Exposure assessment, United Kingdom

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Background

Imidacloprid (IUPAC name: (E)-1-(6-chloro-3-pyridinylmethyl)-*N*-nitroimidazolidin-2-ylideneamine; CAS No. 138261-41-3) is an insecticidal active substance (a.s.) belonging to the group of neonicotinoids [1, 2].

Products containing this a.s. are used as plant protection products (PPPs), as biocidal products (BPs) and as VMPs (veterinary medicinal products). The a.s. as well as products containing Imidacloprid have been assessed under the respective regulatory frameworks, i.e., Directive 91/414/EEC [3] and Regulation (European Commission, EC) No 1107/2009 [4] for PPPs, Directive 98/8/EC [5] and Regulation (European Union, EU) 528/2012 for BPs [6] and Directive 2001/82/EC [7] as amended by Directive 2004/28/EC [8] for VMPs.

Due to the broad usage of Imidacloprid under different regulations, various emissions to natural surface water bodies can be expected and the substance is included in the first Watch List (WL) of substances of emerging concern [9] for regulation under the Water Framework Directive 2000/60/EC (WFD) [10] and the Environmental Quality Standards Directive (EQSD) [11]. The compound is retained in the second Watch List by Commission Implementation Decision (EU) 2018/840 [12]. In the European Environment Information and Observation Network (EIONET) [13] monitoring data for Imidacloprid in the United Kingdom (UK) surface water bodies are published for the years 2016, 2017 and 2018.

In 2017, a report was published containing 2016 monitoring data of five neonicotinoid insecticides, including Imidacloprid, at multiple monitoring sites in British freshwaters [14]. In three samples from urban rivers, Imidacloprid concentrations exceeded the pollution limit for the sum of neonicotinoids as suggested by Morrissey et al. [15]. The authors of the report [14] hypothesised that the use of Imidacloprid as a PPP outdoors is not the reason for increased Imidacloprid concentrations in surface water bodies since the highest levels found were detected in surface waters having no or limited agriculture and forestry activities in their catchments. Instead it was conjectured that the elevated concentrations in the UK surface water bodies were most likely associated with the use of VMPs for pets since Imidacloprid was detected in rivers receiving water from urban areas.

Concerning the use of Imidacloprid as PPP, the substance was included in Annex I of Directive 91/414/EEC on 1 August 2009 [16] and approved under Regulation No 1107/2009 [17]. The agricultural uses in the EU were restricted in 2013 following an evaluation by the European Food Safety Authority (EFSA). The European Commission restricted outdoor uses for seed treatment, soil application and foliar treatment in certain bee-attractive crops such as corn and oilseed rape [18]. The Food and Environment Research Agency (FERA) pesticide usage survey reports only minimal usage of Imidacloprid as a pesticide in the UK in 2016, reporting a total use of Imidacloprid as pesticide amounting to 1 kg and a total area treated of 4 hectares [19]. However, the information published by FERA does not consider all pesticide usages every year and focuses on active substances used most regularly, which does not include Imidacloprid. In addition, the FERA pesticide usage survey does not give the full picture as the biocidal uses (described in the next paragraph) are not reflected. In 2018, the agricultural use of Imidacloprid was further limited to PPP applications in permanent greenhouses provided that the resulting treated crops remain in the premise during their entire life cycle [20]. Several Imidacloprid containing formulations are authorized in the EU for use in permanent greenhouses. However, no Imidacloprid-containing products for PPP purposes are registered in the UK since January 2020 [21].

In the framework of the harmonised approval of biocidal a.s. and authorisations of BPs in the EU, Imidacloprid was included into Annex I to Directive 98/8/EC on 1 July 2013 [22] for Product Type (PT) 18, i.e. insecticides, acaricides and products to control other arthropods. There are 25 Imidacloprid containing BPs registered in the UK (effective 31.10.2019) [23]. The products are authorized for professional and non-professional users to be mainly applied in- and outdoor as baits and window stickers against e.g., cockroaches, ants and flies.

The principle concept for the registration of PPPs and BPs is to first evaluate the a.s. for inclusion into an EU-effective positive list and then to authorize products containing the approved a.s. at the country level. In contrast for VMPs a single-stage assessment of quality, safety and efficacy occurs for individual VMPs, this assessment considers the safety of the a.s. in the context of the use of the product and leads to an overall benefit-risk assessment. Applications for authorization of individual VMPs are made either as an authorization at European level or as authorizations in one or more European countries [24, 25]. As VMPs, Imidacloprid containing products for cats and dogs were first registered in the UK in 1997 [26]. Thereafter, further registrations were granted for spot-on products for cats, dogs, rabbits and ferrets and collar products for cats and dogs [27]. Imidacloprid containing VMP products are exclusively applied topically in spot-on products and collars to eliminate arthropod parasites, for example fleas and ticks [28, 29]. In addition to the direct protection of animals, the spot-on products and collars are also used as protection against certain vector borne diseases e.g. Leishmaniosis [30] and Babesiosis [31, 32] depending on the type of product and other a.s. included in the product. Some spot-on products provide treatment against mixed parasitic infections (e.g. fleas, mites, nematodes and heartworms) and are often used to effectively prevent and treat zoonotic diseases like Dirofilariasis [33, 34]. The total amount of Imidacloprid in veterinary medicines used in 2015 in the UK amounted to 3910 kg according to information released by UK Veterinary Medicines Directorate (VMD) in March 2019 in response to a Freedom of information request.

Whilst in the EU the law requires an environmental risk assessment to be conducted for each VMP as part of the authorisation process [35], there is no EU law or guidance which requires, or sets out the approach to the calculation of potential long-term surface water concentrations resulting from the end-use in companion animals, such as dogs and cats, of topically applied ectoparasiticides [36–38]. Discussions are on-going at European level on whether it is appropriate to evaluate whether the current approach remains scientifically justified [39]. We, therefore, had to develop a new methodology to identify and quantify relevant emissions pathways and evaluate whether concentrations found in surface water and potential alleged risks to aquatic organisms can be caused by use of VMPs [14].

Based on our knowledge of the VMPs including their properties and use we hypothesized that (i) the use as a VMP only contributes to a minor extent to the observed Imidacloprid annual average concentrations found in the monitoring programmed under the framework of the WFD WL, (ii) the use of Imidacloprid as a VMP does not result in surface water concentrations leading to chronic adverse effects to aquatic invertebrate organisms and (iii) Imidacloprid concentrations in the UK surface waters cannot be attributed to a specific end-use of the substance.

For testing the hypotheses, we first identified the most relevant routes of Imidacloprid VMP emissions that might continuously contribute to surface water concentrations and developed a model for each of the relevant scenarios to calculate surface water concentrations. The model calculations are based on the procedures as laid down in the EU Biocidal Products Regulation (BPR) [6] and its technical documents [40, 41]. The calculated predicted environmental concentrations (PECs) in surface water were compared with predicted no-effect concentrations (PNECwater) to assess the chronic aquatic risk due to use of Imidacloprid containing spot-on and collar VMPs. For testing hypothesis (iii), we evaluated measurements for Imidacloprid that have been made in 2016, 2017, and 2018 under the WFD WL. Locations of relevant sampling stations were characterized with reference to the catchment environment and potential sources of Imidacloprid emissions.

Materials and methods

Model development

Rationale

For the aquatic risk assessment of Imidacloprid containing VMPs, i.e., dog and cat spot-on and collar products, we identified relevant emission routes covering the normal use of the product and developed realistic worst-case emission scenarios to assess the risks for surface water organisms. Whilst single washings of pet bedding or washings/bathing of a dog without exposure between two washing events would represent single acute exposures, considering all households connected to one sewage treatment plant (STP) the associated emissions are assumed to happen continuously over time hence leading to continuous exposure. Focus is set on continuous emissions since Imidacloprid monitoring data in the WFD WL shows concentrations at several sampling sites throughout the year, indicating potential long-term exposure, possibly from diffuse emission sources (Table 3).

The development of the calculation model is based on the principles of the environmental risk assessment for BP in the EU as required by ECHA. In the absence of specific EU guidance for veterinary medicines this approach is appropriate as the starting point for modelling due to the similarities between BP and VMPs. For example, they are formulated products which can involve the same active substances, they are used at home, with defined use descriptions and warning statements. The biocidal approach examines emissions arising from the use of a product which enter the aquatic environment via the standard route, i.e. surface water via a standard STP. The STP as an emission source is not considered under the VMP regulation. No scenarios exist for pets, neither under VICH GL6 [36], nor under VICH GL38 [37]. However, in the case of bathing a dog or washing a pets' bedding, the STP is the main source for emission, hence the main entry path into the environment. Shardlow (2017) suggests that insecticides "*… applied to pets will wash off in a variety of circumstances: in rain onto whatever habitat the animal is on, which may result in the pollution of storm drains and water courses* [14]*; when the animal or its bedding is washed* [42]*, which may result in the pollution entering the sewage systems and storm drains and thereby watercourses…*". Some authors suggest a release into wastewater of insecticides that are used in spot-on products [43] or when washing pets' bedding [42]. Therefore, the use of scenarios based on the biocidal approach seems to be appropriate to calculate the predicted environmental concentration of a VMP. The PECs are calculated at the local level i.e. for an individual STP and compared to the PNECs in the concerned environmental compartment [40]. If PEC/PNEC > 1, the substance is considered to be of concern for that specific use and further action has to be taken to mitigate the risk. To predict the environmental concentrations, default values are used in the generic model. Those default parameters, set by the EU Regulators for BPs, are in most cases worst-case since a realistic but conservative assessment is intended. Nevertheless, default values can be overruled to refine the risk assessment when more specific or experimental data is available e.g. for the a.s., product use, or environmental parameters. For the calculations, we have used default parameters and values specified in the technical documents of the BPR [40] and realistic product data are considered. Thus, sales volumes of collars and spot-on products in the UK as well as results from company-owned studies are used to estimate emissions from treated cats and dogs. The PECs for the assessed use of Imidacloprid containing veterinary medicinal spot-on and collar products are compared with the PNECs for Imidacloprid in the surface water compartment. Despite the fact, that concentration limits for surface water are not included in the WFD and no EU-wide EQS is adopted, different chronic aquatic PNECs for Imidacloprid are available and are summarized in the next section.

Chronic aquatic ecotoxicological endpoints for Imidacloprid

As Imidacloprid is not specified in the WFD there is no EU wide EQS set [11]. A number of different PNECwater thresholds are currently in use for Imidacloprid, so we decided to compare the calculated PECs against each of these. The basis of the PNEC is the following set of studies:

With reference to the BPR [6], a PNECwater of $4.8E-03$ µg/L was established after the a.s. evaluation [44]. This value is based on the lowest laboratory effect value which was observed, in a non-standard experimental design, for the mayfly *Caenis horaria* (28d-$EC10=0.024$ µg/L), applying an assessment factor (AF) of 5.

Imidacloprid was included in the first WL, and also in the follow-up second WL [12]. The suggested PNECwater for the second WL is $8.3E-03$ µg/L and was established by Carvalho et al. [45] applying a species-specific data approach.

Whitfield-Aslund et al. [46] used observed NOECs for aquatic invertebrates from higher-tier chronic mesocosm studies which are designed to mimic more realistic conditions than laboratory studies. Based on these NOECs the authors derived a Species Sensitivity Distribution (SSD) for the water organism to determine the Imidacloprid concentration up to which 5% of the most sensitive aquatic taxa are predicted to be affected and potential effects of acute and chronic exposure of aquatic invertebrate communities to Imidacloprid. Toxicity was assessed using refined acute and chronic community-level effect metrics for aquatic invertebrates. The lowest predicted 5% hazard concentration for Imidacloprid was 1.01 µg/L. This results in a PNECwater value of 0.2 µg/L using an AF of 5. These three representative PNECwater values have been compared to the calculated PEC values from the identified scenarios described in the next sections. An overview of the PNEC values is given in Additional file 1: Table S1.

Summary of input data

Several studies were conducted to derive realistic worst-case input parameter for modelling. Stroking tests with VMP treated dogs and treated cats were performed to estimate the transfer of Imidacloprid from fur to textile surfaces [47–51]. The impact of washing and vacuuming on Imidacloprid remains in cat bedding was investigated [52] and two tests were performed with imidacloprid containing collars to investigate emissions into water [53, 54]. Please refer to more details in Additional file 1.

Sales volume data

In addition to studies, actual sales volume figures in the UK have been considered to derive model parameters. The sales data reflect the sales volume of Bayer manufactured Imidacloprid containing veterinary medicines in the UK in 2017.

In 2017 about 8.5 million dogs and 8 million cats were cared for in 27.1 million UK households [55]. Market research shows that on average between 3 and 4 pipettes of Imidacloprid containing Spot-ons are applied per pet and year. Figures on the total number of Imidacloprid containing spot-on pipettes sold for use on cats and dogs in the UK were then divided by a number of pipettes applied per dog and cat in a year respectively to calculate the number of dogs and cats treated with spot-ons per year. These numbers can be used to calculate the fraction of all dogs and cats in the UK that were protected with spot-ons containing Imidacloprid in 2017. These calculations reveal that almost half of the dogs and one-third of the cats in the UK were protected with spot-ons containing Imidacloprid. Regarding Seresto it is assumed that one collar is used per year and pet in accordance with the registered label and thus sales figures for 2017 reflect the number of dogs and cats treated per year with the collar. Seasonality of use of the spots-ons is considered as well (next section).

Taking into account the different imidacloprid content in the products the total amount of imidacloprid used in veterinary medicines sold in the UK was about 4000 kg in 2017.

Market survey

A market research survey among cat and dog owners in the UK was commissioned to SKOPOS market research by the sponsors to estimate realistic parameters. 307 dog owners and 301 cat owners were included. The fieldwork was conducted between October and December 2018.

The inclusion criteria used for the qualification of the pet owners are detailed in Additional file 1. The questions and replies relevant for this modelling work are presented in Additional file 1: Tables S2–S4.

For seasonality of use, survey data was used (see Additional file 1: Table S4). The responses showed that the use of Imidacloprid containing spot-ons for dogs was most frequent in the months of July and August (approximately 10.6% each). For cats, the most frequent use was in September and October (approximately 9.9% and 13.4%, respectively). This information was then used to determine the worst-case frequency of use per month for spot-on products (F_{use}): 0.11 for dogs and 0.13 for cats. Please see also in "Results" section.

Identification and description of scenarios relevant for chronic emissions

Long-term exposure of Imidacloprid from spot-on products or collars to surface water is only conceivable if there are a very large number of treated companion animals combined with a substantial release of Imidacloprid from each single treatment, all draining to one sewer and the same adjacent STP. Three different scenarios for the release of Imidacloprid residues from treated animals are identified and considered which are believed to cover the vast majority of emissions to STPs.

In households, cats and dogs usually have designated resting and sleeping places in the form of soft bedding such as soft baskets, blankets and mats. Here, Imidacloprid may be transferred from the treated animal to the surface of the bedding materials. The term used in the BPR to describe this is "abrasion" [57] so this is the term used here, although the mechanism (physical and/or chemical) may be abrasion and/or adsorption–desorption. The washing of these bedding materials may lead to residual emissions to the wastewater. In the framework of BPR, the emission due to washing of exposed textiles is also considered relevant for indoor applied insecticides against fleas or bed bugs or for the application of repellents to cats and dogs [41, 56, 57]. The second relevant scenario is the release of Imidacloprid residues to wastewater when treated dogs are washed or bathed by their owners. Some dogs are bathed by their owners on a regular basis whilst others may only be partially washed, for example lower legs only being washed down following a muddy walk. The release of applied substances during washing is also addressed under BPR, e.g., for disinfectants and insect repellents applied to human skin [57, 58]. Relevant emissions may also occur when treated dogs are walked outdoors during heavy rain events. Here, rainwater may saturate the treated pelt and droplets may enter paved surfaces like sidewalks, which are drained to the sewer. Emissions by rainwater are also relevant for insecticides applied outdoors onto terraces or to the perimeter of houses [41].

In summary, three relevant scenarios were identified; Scenario 1: Washing of pet bedding; Scenario 2: Washing/bathing of dogs; Scenario 3: Walking dogs in the rain. Cats and dogs are only considered in the model. Whilst some of the spot-on products are also authorised for use in rabbits and ferrets, in terms of volume of units sold these are of minor importance. Furthermore, these animal species are usually kept on disposable bedding materials, and like cats, are rarely washed or bathed, or walked outdoors.

Emission calculations

Three scenarios have been identified for emissions to surface waters via STPs. With respect to the three selected scenarios, each pathway is examined independently. This approach allows the identification of the worst-case source for discharge.

For each assessed scenario, independent calculation models have been developed by using both, general and scenario specific parameters. Derivation of the relevant parameters is described below and the final input values are summarized in Table 1 in "Results" section. As otherwise noted, the derivation of some parameters is based on studies from the sponsor. Sales figures at the product level are not disclosed for confidentiality reasons. However, in 2017 the total number of units (1 collar = 1 unit, 1 spot-on pipette = 1 unit) of VMPs sold by Bayer in the UK was in the order of 22 million. The sponsor conducted a pet owner survey in 2018. The questions and outcome are detailed in the previous section "market survey" and in Additional file 1. The results are summarised in Additional file 1: Table S2–S4.

Following parameters, assumptions and approaches are used according to the BPR approach [40]:

- Number of households, which are connected to the same STP (N_{houses}): 4000 [41]
- The effluent discharge rate for a STP ($EFFLUENT_{STP}$) of 2,000,000 L/day
- The dilution factor of 10 from the STP effluent into the adjacent receiving river water (DILUTION)
- The calculation of the PECs at the local level for one STP per day. The ESD for PT 19 [57] was used in the model to determine potential emission from the washing of pet bedding as the emission route from this scenario is considered similar to washing in private households of textiles treated with biocidal products (e.g. repellents).

Table 1 Scenario-independent and scenario-specific input parameters for the release of Imidacloprid from topically applied VMPs

Parameter	Nomenclature	Spot-on		Collars		Unit	References
		Dogs	Cats	Dogs	Cats		
Parameter not related to specific scenario							
Fraction of houses treating a dog/cat	$F_{houses,treating}$	0.14	0.10	7.63 *E*−03	2.31*E*−03	(–)	Equation 2
Number of treated animals per STP	$N_{dog/cat,treated/STP}$	558	400	31	9	(–)	Equation 1
Active substance used for all cats and dogs considering multiple applications per year and weight differentiation	$Q_{ai,dog/cat\_year}$	389	81	93	12	(g/year/STP)	Additional file 1: Eq. S1a
Frequency of use per day	$F_{use,spot\text{-}on}/F_{use,collar}$	3.5*E*−03	4.5*E*−03	4.2*E*−03	4.2*E*−03	(day^{-1})	Additional file 1: Eq. S2a (spot-on)
Amount of a.s. used maximal per day	$Q_{ai,dog/cat\_day\_spot\text{-}on}/Q_{ai,dog/cat\_day\_collar}$	1.38	0.36	0.39	0.048	(g/day/STP)	Equation 4
Scenario 1: Washing of pet bedding							
Fraction for abrasion	F_{abr}	0.20	0.20	0.01	0.01	(–)	a
Fraction being released due to washing	$F_{washing}$	0.50	0.50	0.50	0.50	(–)	a
Fraction released to waste-water	F_{water}	0.10	0.10	0.005	0.005	(–)	Equation 5
Simultaneity factor	F_{sim}	0.10	0.09	0.10	0.09	(–)	a
Scenario 2: Washing/bathing of dogs							
Fraction being released due to washing/bathing	$F_{washing}$	0.50	n.r	0.20	n.r	(–)	a
Fraction remaining in collar	F_{collar}	n.r	n.r	a	n.r	(–)	b
Fraction released to waste-water	$F_{water\_spot\text{-}on}/F_{water\_collar}$	0.50	n.r	0.08	n.r	(–)	Equations 11, 12
Simultaneity factor	F_{sim}	0.13	n.r	0.13	n.r	(–)	a
Scenario 3: Walking dogs in rain							
Fraction being released due to rain	F_{rain}	0.20	n.r	0.02	n.r	(–)	a
Fraction entering the same STP	F_{STP}	0.50	n.r	0.50	n.r	(–)	a
Fraction released to waste-water	F_{water}	0.10	n.r	0.01	n.r	(–)	Equation 15
Fraction of owners walking dogs in the rain	$F_{walking}$	0.31	n.r	0.31	n.r	(–)	a

n.r. not relevant

[a] Additional file 1

[b] Data unpublished, confidential

The model input parameters for the quantity of Imidacloprid released from treated dogs and cats are calculated per day in accordance with the BPR approach.

Within the surface water, the sediment is exposed as well. However, according to the BPR Assessment Report of Imidacloprid [44] "*there are no tests with bentic organisms available [..] and therefore the PNECsediment is derived from the PNECwater using the equilibrium partitioning method (EPM)….*". Since the calculation of both PNECsediment and PECsediment via the EPM are based on both PNECwater and PECwater, the results for the sediment PEC/PNEC ratios and the conclusions therein are equal to those for the surface water. Therefore, no results for the sediment are reported in the following and the later discussion focuses on the surface water compartment, as the sediment is covered by the surface water assessment.

For the calculation of Imidacloprid surface water concentrations adjacent to a STP, it is important to estimate the number of spot-on and the number of collar treated cats and dogs per STP. This is done using the following equation:

$$N_{dog/cat,treated/STP} = N_{houses} \cdot F_{houses,treating} \tag{1}$$

with N_{houses} as the number of default 4000 houses being connected to the same standard STP [41] and with $F_{houses,treating}$ being the fraction of houses treating a cat/dog with a spot-on/collar assuming that only a certain number of households own a pet.

$F_{houses,treating}$ was calculated with the below equation based on 2017 sales data from the sponsor:

$$F_{houses,treating} = N_{dog/cat,spot\ on}/N_{households,UK} \text{ or } N_{dog/cat,collar}/N_{households,UK} \quad (2)$$

The number of households in the UK $N_{households,UK}$ is 27.1 M. The number of dogs or cats treated with spot-ons or collars in the UK ($N_{dog/cat,spot\ on}$ and $N_{dog/cat,collar}$) is based on sales data from the sponsor (number of pipettes of Imidacloprid spot-on products sold per year, $N_{sold,spot\ on}$) and the results of the pet owners survey (number of pipettes applied per dogs or cats; $N_{appl/year\_dog/cat\_spot\ on}$) described in the methodology and calculated as:

$$N_{dog/cat,spot\ on} = N_{sold,spot\ on}/N_{appl/year\_dog/cat\_spot\ on} \quad (3)$$

Due to the long-term efficacy of the collar [65], it is assumed that one collar is applied per year and thus, $N_{appl/year\_dog/cat\_collar}$ is assumed to be 1.

Sales volume data $N_{sold,spot\ on}$ of the sponsor differentiate spot-on product sales by Imidacloprid content according to four different dog weights and two different cat weights. Similarly, it is differentiated between marketed dog collars containing different active amounts for two dog weight groups while cats collars are not differentiated. The sum of the sales volumes multiplied by the corresponding Imidacloprid content of the products for the different weight groups results in the quantity of the active substance used in spot-ons/collars for dogs and cats in the UK in 2017. The Quantity per STP (Q_{ai_dog/cat_year}) is calculated by multiplication with the fraction of houses connected to one STP (N_{houses}) and all household in the UK ($N_{households,UK}$).

$N_{dog/cat,treated/STP}$ is used to derive the annual amount of Imidacloprid being released from all cats and dogs to the same STP (Q_{ai_dog/cat_year}) summing up the applied Imidacloprid amounts for different pet weight classes (for dogs < 4 kg, 4–10 kg, 10–25 kg, > 25 kg and for cats < 4 kg and 4–8 kg), the percentage of cats/dogs living in the UK per weight class and a multiple seasonal application of the product per year ($N_{appl/year\_dog/cat\_spot\ on}$).

Due to different weather conditions and parasite pressure throughout the year, it can be expected, that the frequency of application of spot-ons varies according to the season and month. The market survey previously mentioned revealed a monthly seasonality for the application of spot-on products. For worst-case considerations, the month with the highest use frequency based on the seasonality was included in the model with the fraction of use ($F_{use\text{-}month}$). F_{use} is used to calculate the annual amount of Imidacloprid being released from all cats and dogs spot-ons to the same STP (Q_{ai_dog/cat_year}) on a daily basis applying the following equation.

$$Q_{ai,dog/cat\_day} = Q_{ai,dog/cat\_year} \cdot F_{use\_month}/30 \text{ days} \quad (4)$$

For collars, F_{use} is uniformly set to 1/240 to calculate the quantity per day by dividing the quantity of Imidacloprid in the collar by 240 days, the registered duration of efficacy for all collars.

In the following sections, the model parameters of each individual scenario and their derivation are described. The final input values are summarized in Table 1 in "Results" section.

Scenario 1: Washing of pet bedding

Emission of Imidacloprid from spot-on or collar treated animals to the surface water compartment via STP may be due to abrasion from treated animals to pet bedding and washing of those textiles and subsequent release of wastewater to the STP.

It is assumed that Imidacloprid is only partly transferred from the animal skin to the pet bedding, i.e. fraction for abrasion (F_{abr}). Studies to estimate the Imidacloprid transfer to textiles following topical applications of various spot-on products or collars on cats and dogs have been conducted ([47–51], see additional information).

A complete release of the substance from the exposed textile during washing of the textile is unlikely because a significant part of the a.s. is removed by vacuuming which is usually done more frequently than washing. The fraction is considered as $F_{washing}$ in the model. A study was conducted on the influence of washing and vacuuming on Imidacloprid levels in cat bedding following the application of spot-on products [52]. For further study details, please refer to Additional file 1. Furthermore, the sponsor conducted a survey to collect data on the manner and frequency of cleaning dogs and their bedding, i.e. vacuuming or washing bedding material.

The fraction for abrasion (F_{abr}) and the fraction being released due to washing ($F_{washing}$) are multiplied to account for an overall fraction being released to wastewater (F_{water}) by Eq. 5:

$$F_{water} = F_{abr} \cdot F_{washing} \quad (5)$$

Since all cat and dog owners will presumably not wash pets' bedding the same day, emissions to the wastewater are diffuse. To account for this behaviour, a simultaneity factor (F_{sim}) has been established according to the Emission Scenario Document for biocidal insecticides used for household purposes [43]. F_{sim} = Sum (% dog/cat owners washing per day × frequency of washing (% answers from the survey for each frequency in Additional file 1: Table S5))/10,000.

The local concentration of Imidacloprid in surface water from both spot-on product and collar use can thus be calculated by the amount being discharged into wastewater and being released via the standard STP to surface water according to the following:

$$\text{Clocal}_{\text{water,spot-on}} = (Q_{\text{ai,dog/cat\_day\_spot-on}} \cdot F_{\text{water}} \cdot F_{\text{sim}})/(\text{EFFLUENT}_{\text{STP}} \cdot \text{DILUTION}) \quad (6)$$

$$\text{Clocal}_{\text{water,collar}} = (Q_{\text{ai,dog/cat\_day\_collar}} \cdot F_{\text{water}} \cdot F_{\text{sim}})/(\text{EFFLUENT}_{\text{STP}} \cdot \text{DILUTION}) \quad (7)$$

The surface water concentrations resulting from both spot-on and collar use are summed up (Eq. 8) to be compared with the PNEC:

$$\text{Clocal}_{\text{water}} = \text{Clocal}_{\text{water,spot-on}} + \text{Clocal}_{\text{water,collar}} \quad (8)$$

Scenario 2: Washing/bathing of dogs

In Scenario 2, emissions of Imidacloprid to surface water via STP may result from washing or bathing treated dogs.

It is assumed here that only a fraction of dogs are washed at the same time in one STP catchment. Therefore, a simultaneity factor (F_{sim}) specific for Scenario 2 is included. F_{sim} is based on a survey by the sponsor on the frequency that dog owners wash or bath their dogs per day, with and without shampoo.

$$F_{\text{sim,shampoo/no shampoo}} = \text{Sum}\ \big(\%\text{dog/cat owners washing dogs per day} \cdot \text{frequency of washing/bathing dogs}\ (\%\ \text{answers from the survey for each frequency in Additional file 1: Table A5})\big)/10,000 \quad (9)$$

$$F_{\text{sim}} = F_{\text{sim,shampoo}} + F_{\text{sim,shampoo/no shampoo}} \quad (10)$$

Furthermore, it is assumed that only a proportion of the applied a.s. enters wastewater via washing/bathing of the treated dog ($F_{washing}$). This is based on expert judgement and considering supporting data such as the immersion study for dogs wearing collars [53, 54]. Depending on the application mode either via spot-on or collar, the fraction of Imidacloprid being released to the wastewater (F_{water}) varies.

Even though dog owners are unlikely to bathe or wash dogs on the same day as applying a spot-on, as a worst-case assumption the F_{water} figure is not further refined, so Eq. 11 applies:

$$F_{\text{washing}} = F_{\text{water\_spot-on}} \quad (11)$$

For the release of Imidacloprid from collars to the washing water, immersion studies with dogs wearing collars or having worn collars were conducted [53, 54]. Less than 1% of the collar inventory was found in the immersion water and providing a high margin of safety, F_{water_collar} was set. Additionally, the release of Imidacloprid inventory from the collar onto the pets (F_{collar}) was considered in Scenario 2 of the model. The fraction remaining in the collar (F_{collar}) was determined when it is disposed of in the local waste. To account for the release fraction of Imidacloprid from the collar treated pet to the wastewater via washing/bathing, Eq. 12 has been established:

$$F_{\text{water\_collar}} = (1 - F_{\text{collar}}) \cdot F_{\text{washing}} \quad (12)$$

The total concentration of Imidacloprid in surface water upon release from washing/bathing to the standard STP and surface water [41] is calculated for both spot-on and collar treatment using the following Eqs. 13 to 14:

$$\text{Clocal}_{\text{water,spot-on}} = (Q_{\text{ai,dog\_day\_spot-on}} \cdot F_{\text{water\_spot-on}} \cdot F_{\text{sim}}) /(\text{EFFLUENT}_{\text{STP}} \cdot \text{DILUTION}) \quad (13)$$

$$\text{Clocal}_{\text{water,collar}} = (Q_{\text{ai,dog\_day\_collar}} \cdot F_{\text{water\_collar}} \cdot F_{\text{sim}}) /(\text{EFFLUENT}_{\text{STP}} \cdot \text{DILUTION}) \quad (14)$$

The surface water concentrations resulting from both spot-on and collar use are summed up (Eq. 8) to be compared with the PNEC.

Scenario 3: Walking dogs in the rain

The third scenario examines the release of Imidacloprid from the treated dog when being walked during a heavy rainfall event. Droplets of the soaked and saturated pelt may enter paved surfaces which are connected to the standard STP.

To account for a more realistic emission scenario, three fractions have been introduced in the model for Scenario 3, i.e., F_{rain}, F_{STP} and $F_{walking}$.

To account for the fraction of Imidacloprid being released from the treated pelt due to rain F_{rain}, results from two immersion tests with the collars and with dogs wearing or having worn collars have been considered in the model [53, 54].

When Imidacloprid residues are washed off the dogs' pelt from a walk in the rain, they may end up on the surface underneath. According to the regulatory approach for biocides, those surfaces are either unpaved surfaces, i.e. the soil compartment directly, or paved, i.e. surfaces which are connected to the sewer and adjacent standard STP. Only the emissions to the paved surfaces to the STP are relevant for Scenario 3. Considering survey data which show that half of the dog owners walk their dogs on paved ground, a fraction of Imidacloprid is set to account for the release to the STP (F_{STP}).

The model further considers a fraction of dog owners walking their dogs in heavy rainfall events which would completely wet the dogs' pelt ($F_{walking}$). This is supported by the results of a survey conducted by the sponsor.

The fractions F_{rain}, F_{STP} and $F_{walking}$ are considered in the following for the estimation of the Imidacloprid release when walking the dogs in the rain. The fraction being released to wastewater (F_{water}) is calculated for spot-on products using Eq. 15 and the concentration of Imidacloprid in surface water using Eq. 16. For collar products, the concentration of Imidacloprid in the surface water is calculated using Eq. 17:

$$F_{water} = F_{rain} \cdot F_{STP} \tag{15}$$

$$\mathrm{Clocal}_{water,spot\text{-}on} = (Q_{ai,dog\_day\_spot\text{-}on} \cdot F_{water} \cdot F_{walking}) / (\mathrm{EFFLUENT}_{STP} \cdot \mathrm{DILUTION}) \tag{16}$$

$$\mathrm{Clocal}_{water,collar} = (Q_{ai,dog\_day\_collar} \cdot F_{water} \cdot F_{walking}) / (\mathrm{EFFLUENT}_{STP} \cdot \mathrm{DILUTION}) \tag{17}$$

The surface water concentrations resulting from both spot-on and collar use are summed up (Eq. 8) to be compared with the PNECs.

Analysis of monitoring sites and measured Imidacloprid concentrations in surface water bodies

Imidacloprid concentrations at various monitoring locations in the UK were determined as per the WL framework according to WFD and are provided on EIONET [13]. The reported concentrations were compared with the modelled results. Information provided in the WL Summary document concerning the monitoring sites were considered in the analysis and interpretation of monitoring results [59]. Unless otherwise noted, the LOQ for all Imidacloprid measurements in the UK was 0.001 µg/L.

A total of 29 sites are considered (Fig. 1). The spatial locations (latitude/longitude) of sampling points were extracted from the Catchment Data Explorer of the Environment Agency [60] and the Waterbase data collection by the European Environment Agency [61]. On this basis, the exact spatial locations of the stations could be determined and the following map of all relevant sampling points was prepared using QGIS 2.18 taking the special locations, data from GADM database (administrative boundaries map) [62] and OpenStreetMap (river network map) [63] into account.

The measured Imidacloprid concentrations at the monitoring sites from the years 2016, 2017 and 2018 are summarized in Table 3. Next to arithmetic mean concentrations, the minimum and maximum concentrations are listed. Where levels of Imidacloprid were detected but below the LOQ for the purpose of calculating the arithmetic mean, the levels were assumed to be half of the LOQ.

Surrounding areas of the monitoring stations were characterized, i.e., catchment environment and potential substance emissions, by visual observation using Google Maps. Monitoring stations impacted by urban wastewater treatment plants were further analysed regarding the size and capacity of the relevant treatment plants. Details were taken from the Urban Waste Water Treatment Directive site of the UK [64].

Two locations, i.e., Eden and Windermere, are not included in Table 3 but shown in Fig. 1 for completeness. Although these locations are described in the summary document of WF watch list sampling [59], no analytical measurements are available [13]. In contrast, two other locations, i.e., Ivel and Nene, are not described and further information on land use is not available [59]. Therefore, these locations are not shown in Fig. 1, but listed in Table 3 as Imidacloprid was detected at these locations [13].

Results

Derived parameters for modelling approach

For the estimation of the potential release of topically applied Imidacloprid from companion animals, realistic worst-case input parameters were deduced for the identified scenarios, i.e., washing of pet bedding, washing/bathing of dogs and walking dogs in the rain. In addition to default values specified in the technical documents of

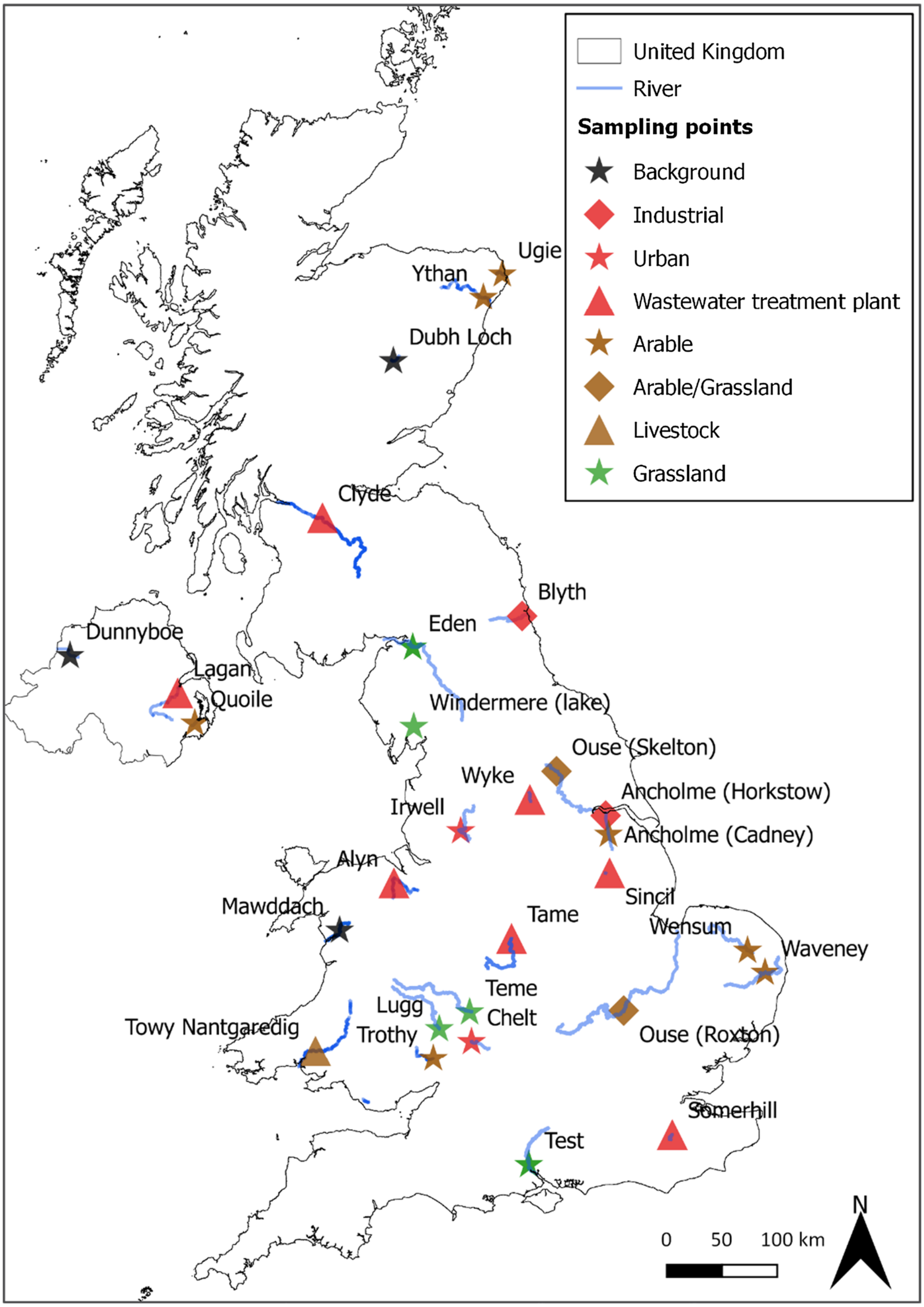

Fig. 1 Location and land use of watch list sampling points in the UK. [1]Total amount of applied Imidacloprid per animal per day

the BPR [40], confidential market data and experimental studies were added for the parametrisation of the model. Information details are further explained in an additional file to this publication. Scenario-independent and scenario-specific input parameters for modelling are summarized in Table 1.

The maximum amount of Imidacloprid used on dogs and cats in the catchment area of the same STP per day from its use as topically applied VMP ranges between 0.048 and 1.38 g, resulting from the number of treated animals per STP and the amount of Imidacloprid used for the treatments ($Q_{\text{ai,dog/cat\_day\_spot-on}}/Q_{\text{ai,dog/cat\_day\_collar}}$). The maximum fraction of houses in the UK treating a cat or dog ($F_{\text{houses treating}}$) on a single day is up to 0.14 resulting in a maximum of 558 dogs being treated in the catchment area of one STP ($N_{\text{dog/cat,treated/STP}}$). The annual amount of Imidacloprid being released from all cats and dogs to the same STP ($Q_{\text{ai\_dog/cat\_year}}$) is between 12 g a.s./year/STP for cats treated with collars and 389 g a.s./year/STP for spot-on treated dogs. This amount is further refined with the frequency of use.

The survey on the seasonality of product use revealed that Imidacloprid containing spot-on pipettes for dogs are mostly applied in July and August. In each of these months, 10.6% of the yearly used spot-ons containing Imidacloprid is applied. This leads to a daily fraction $F_{\text{use,spot-on}}$ of 3.5E−03 (assuming an average of 30 days/month). For cats, the application of Imidacloprid spot-on products is highest in October with 13.4% resulting in a daily fraction $F_{\text{use,spot-on}}$ of 4.5E−03 (assuming an average of 30 days/month). Seasonality for collars can be excluded due to their long-term residual efficacy of up to 8 months [65, 66]. Consequently, $F_{\text{use,collar}}$ per day for collars is 4.2E−03 for both, cats and dogs (1 collar per 240 days).

For Scenario 1 (washing of pet bedding), the fraction of the applied a.s. that is transferred to pet beddings (F_{abr}) is 0.2 for spot-on products and 0.01 for collar products. For estimating the fraction of a.s. released by the washing of pet bedding F_{washing}, results of a study evaluating the influence of washing and vacuuming on Imidacloprid remaining in cat beddings were considered. It was demonstrated, that washing eliminated completely the a.s. concentration in the cloth whereas vacuuming led to a 50% decrease. Furthermore, a survey on the manner of cleaning pet bedding revealed that vacuuming is done more frequently compared to the washing of pet bedding. The responses showed that the mode value for vacuuming is 42% on a weekly basis whereas it is 43% and 38% on a monthly basis for washing dog and cat bedding respectively (Additional file 1: Table S2). In other words, vacuuming is usually much more frequent than the washing of beddings. Based on that, the fraction being released due to washing (F_{washing}) is set to 0.5 since vacuuming is normally done in between each washing of pet bedding.

For scenario 2 (washing/bathing of dogs), fractions of 0.5 (spot-on, $F_{\text{water\_spot-on}}$) and 0.2 (collar, $F_{\text{water\_collar}}$) are considered for the proportion of a.s. entering the wastewater via washing/bathing of the treated dog. The release fraction for collars includes a significant fraction of Imidacloprid remaining in the collar (F_{collar}) during its 8 month service life according to information by the authors. Simultaneity factors (F_{sim}) of 0.1 for dogs and 0.09 for cats were derived from a survey conducted by the sponsors and are used as inputs for Scenario 1. For Scenario 2, a value of 0.13 is used (Additional file 1: Tables S5, S6).

For the fraction for release due to rain (F_{rain}) relevant for scenario 3, a value of 0.02 is considered for collars taking results from immersion tests into account. For spot-on products, a conservative value of 0.2 is used. A conducted survey revealed that more than half of all dog owners walk their dogs on paved and unpaved surfaces at almost equal shares. Therefore, a F_{STP} value of 0.5 for emissions to paved surfaces is used. The parameter F_{walking} of 0.31 also shows that the fraction of dog owners walking their dogs during heavy rainfall events is limited (Additional file 1: Table S3).

Taking all derived fractions for Scenario 1 into account and comparing this with the total amount of applied a.s. per animal, 0.96% of the inventory, i.e., a.s. applied per day, is emitted for spot-on products and 0.05% for collars to one STP (Fig. 2). For Scenario 2, the amount is higher with 6.68% for spot-on products and ca. 1% for collars. For Scenario 3, the values with 3.1% for spot-on products and 0.31% for collars are comparable with those derived for Scenario 2.

Modelling results

The developed calculation model was used to calculate surface water concentrations. Three scenarios for the release of Imidacloprid residues from treated animals were identified and considered relevant. The calculated concentrations in surface water (PECwater) for the assessed worst-case scenarios are shown in Table 2. The calculated PEC values are compared with the three PNECwater values. According to the BPR framework, PEC/PNEC-ratios greater than 1 indicate an unacceptable risk for the respective environmental compartment [40].

For Scenario 1, summing up local surface water concentrations for cats and dogs being treated with spot-on products as well as collars yields a local concentration in surface water of 8.4E−04 µg/L. Higher concentrations are calculated for Scenario 2 with 4.81E−03 µg/L and Scenario 3 with 2.2E−03 µg/L. The PNEC/PNEC-ratios range between 4.2E−03 and 0.17 for Scenario 1, 0.02 and 1 for Scenario 2 and 0.01 and 0.46 for Scenario 3.

Discussion

Identification of relevant emission scenarios for continuous aquatic exposure

Three emission paths were identified covering continuous environmental emissions from the use of topical

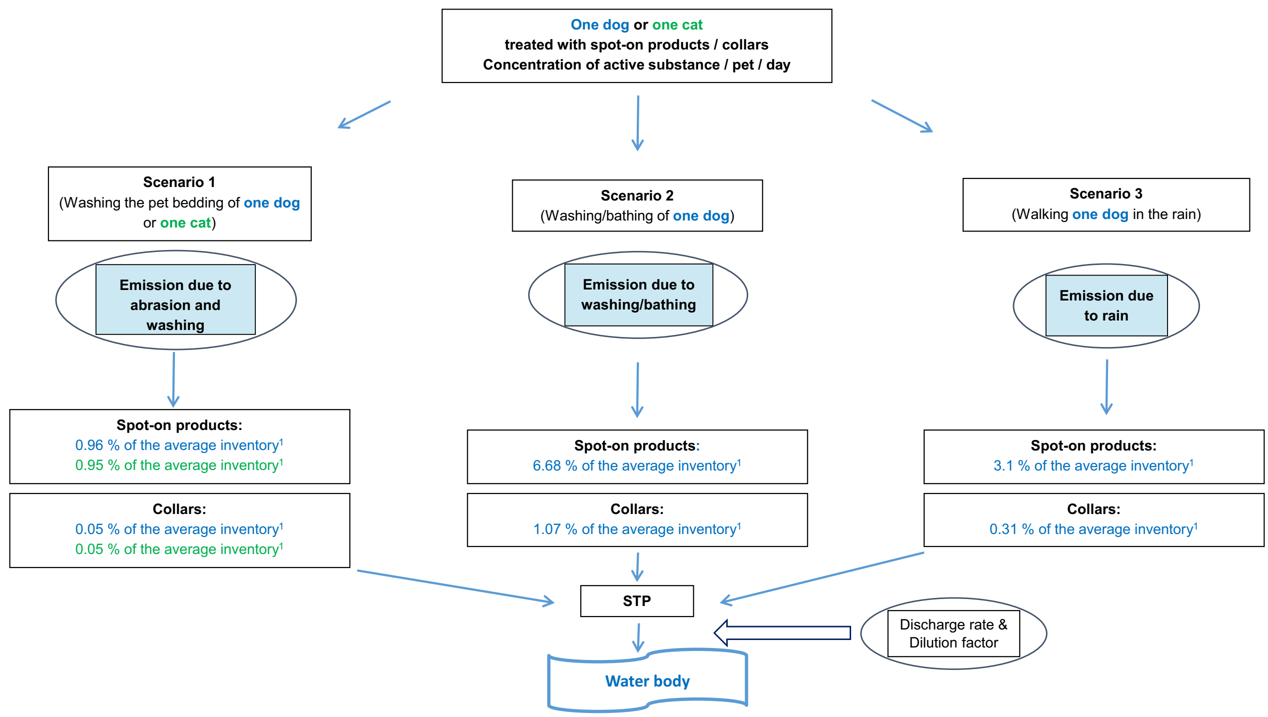

Fig. 2 Emission pathway flow chart. [1]Total amount of applied Imidacloprid per animal per day

Table 2 PEC/PNEC-ratios for surface water and the use of Imidacloprid spot-on and collar products in three relevant worst-case scenarios

Scenario	PECwater (μg/L)	PNECwater (μg/L)	PEC/PNEC-ratios
1. Washing of pet bedding	8.40*E*−04	4.80*E*−03[a]	0.17
		8.30*E*−03[b]	0.10
		0.2[c]	4.20*E*−03
2. Washing/bathing of dogs	4.81*E*−03	4.80*E*−03[a]	1.00
		8.30*E*−03[b]	0.58
		0.2[c]	0.02
3. Walking dogs in the rain	2.20*E*−03	4.80*E*−03[a]	0.46
		8.30*E*−03[b]	0.26
		0.2[c]	0.01

[a] [44]

[b] [45]

[c] [46]

applied VMPs. Based on the methodology for biocidal environmental risk assessments, a model was developed to calculate surface water concentrations for the identified scenarios, i.e. the washing of dog and cat pet bedding, washing/bathing of dogs, and walking dogs in the rain. In addition, one further conceivable chronic scenario is suggested in the literature and this concerns the release from hand/cloth washing after the user applies the VMP or subsequent stroking of the pet [67]. This is not considered likely to be a significant emission path considering that the VMPs are only applied at a maximum frequency of once per month and taking account of the user warning statements on the labels e.g., Advocate spot-ons state "*After application do not stroke or groom animals until the application site is dry*" [68]. Furthermore, in a stroking study the maximum amount of substance transferred to textile observed was 10% of the applied Imidacloprid.

Table 3 Imidacloprid concentrations determined at various sampling locations in the framework of the European Watch List

Sampling location	Full name of sampling location	Land use	Spatial location (latitude/longitude)	Mean imidacloprid concentrations in µg/L [number of measurements]			Minimum concentration of imidacloprid in µg/L			Maximum concentration of imidacloprid in µg/L		
				2016	2017	2018	2016	2017	2018	2016	2017	2018
England												
Sincil	Sincil Dyke Washingborough	Wastewater treatment plant	53.225671, − 0.480368	0.035 [2]	0.076 [1]	0.05 [3]	0.01	0.076	0.036	0.059	0.076	0.059
Somerhill	Somerhill Stream Old Forge FM	Wastewater treatment plant	51.162241, 0.278286	0.14 [2]	0.19 [1]	0.14 [5]	0.089	0.19	0.074	0.18	0.19	0.2
Tame	River Tame—U/S Coleshill stw	Wastewater treatment plant	52.520587, − 1.718607	0.037 [2]	0.054 [1]	0.07 [3]	0.012	0.054	0.067	0.062	0.054	0.074
Wyke	Wyke Beck below Knostrop Works FE	Wastewater treatment plant	53.771364, − 1.475679	0.044 [2]	n.a	n.a	0.026	n.a	n.a	0.061	n.a	n.a
Chelt	River Chelt Princess Elizabeth Way	Urban	51.912862, − 2.099967	0.015 [2]	0.0097 [1]	n.a	0.001	0.0097	n.a	0.03	0.0097	n.a
Irwell	River Irwell at Old Ringley Bridge	Urban	53.543906, − 2.358737	0.012 [1]	n.a	0.023 [1]	0.012	n.a	0.023	0.012	n.a	0.023
Ancholme (Horkstow)	R.Ancholme Horkstow Bottom	Industrial	53.658336, − 0.528363	0.008 [2]	0.0079 [1]	n.a	0.004	0.0079	n.a	0.012	0.0079	n.a
Blyth	Blyth at Bedlington Bridge	Industrial	55.126473, − 1.583458	0.0005 [1]	0.0032 [1]	n.a	0.001	0.0032	n.a	0.001	0.0032	n.a
Ancholme (Cadney)	R.Ancholme Cadney Bottom	Arable	53.512942, − 0.491962	n.a	0.0051 [3]	n.a	n.a	0.0041	n.a	n.a	0.0063	n.a
Waveney	R.Waveney Ellingham Mill	Arable	52.471099, 1.479204	0.019 [51]	0.014 [24]	0.01 [11]	0.005	0.0068	0.004	0.074	0.036	0.024
Wensum	R.Wensum Seet Briar RD.BR	Arable	52.638365, 1.258888	0.015 [52]	0.011 [21]	0.0078 [17]	0.0065	0.0084	0.0038	0.026	0.028	0.01
Ouse (Roxton)	River Ouse Roxton Lock	Arable/Grassland	52.166844, − 0.306319	0.049 [35]	0.029 [35]	0.028 [27]	0.01	0.015	0.0047	0.082	0.053	0.046
Ouse (Skelton)	River Ouse at Nether Poppleton (Skelton)	Arable/Grassland	53.991187, − 1.13455	0.014 [21]	0.0049 [4]	0.031 [3]	0.001	0.0029	0.0016	0.11	0.0062	0.083
Lugg	River Lugg at Mo	Grassland	52.033862, − 2.628223	n.a	0.0050 [7]	n.a	n.a	0.0017	n.a	n.a	0.0016	n.a
Teme	River Teme at Powick	Grassland	52.170057, − 2.241934	0.007 [1]	0.021 [1]	n.a	0.007	0.021	n.a	0.007	0.021	n.a
Test	River Test Longbridge	Grassland	50.958959, − 1.495922	0.0086 [1]	0.0058 [1]	n.a	0.0086	0.0058	n.a	0.0086	0.0058	n.a
Ivel	R.Ivel Tempsford Depot Ft.Br	n.a	52.165758, − 0.303948	n.a	n.a	0.045 [33]	n.a	n.a	0.013	n.a	n.a	0.093
Nene	R.Nene Wansford Old Rd.Br	n.a	52.579088, − 0.414965	n.a	n.a	0.028 [38]	n.a	n.a	0.0093	n.a	n.a	0.047
Wales												
Mawddach	River Mawddach Ty'n Y Groes Hotel Bridge	Background	52.792951, − 3.885728	0.0005 [1]	No access	0.0005 [1]	0.001	No access	0.001	0.001	No access	0.001

Table 3 (continued)

Sampling location	Full name of sampling location	Land use	Spatial location (latitude/longitude)	Mean imidacloprid concentrations in μg/L [number of measurements]			Minimum concentration of imidacloprid in μg/L			Maximum concentration of imidacloprid in μg/L		
				2016	2017	2018	2016	2017	2018	2016	2017	2018
Alyn	River Alyn at Ithels Bridge	Wastewater treatment plant	53.100250, − 2.912500	n.a	No access	0.059 [1]	n.a	No access	0.059	n.a	No access	0.059
Trothy	Trothy at Onen	Arable	51.827378, − 2.832079	0.0012 [1]	No access	0.0005 [1]	0.0012	No access	0.001	0.0012	No access	0.001
Towy Nantgaredig	Towy Nantgaredig, near Carmarthen	Livestock	51.8608 − 4.18971	0.0005 [1]	No access	0.0005 [1]	0.001	No access	0.001	0.001	No access	0.001
Scotland												
Dubh Loch	Dubh Loch Outlet	Background	56.929703, − 3.254838	0.0073 [2]	n.a	n.a	0.001	n.a	n.a	0.014	n.a	n.a
Clyde	River Clyde	Wastewater treatment plant	55.8523, − 4.24593	0.0019 [2]	0.009 [1]	0.0005 [1]	0.001	0.009	0.001	0.0033	0.009	0.001
Ugie	River Ugie	Arable	57.523, − 1.83385	0.0005 [1]	n.a	0.0005 [1]	0.001	n.a	0.001 [1]	0.001	n.a	0.001 [1]
Ythan	River Ythan	Arable	57.3637, − 2.07227	0.0005 [1]	n.a	0.0005 [1]	0.001	n.a	0.001 [1]	0.001	n.a	0.001 [1]
North Ireland												
Dunnyboe	Dunnyboe Burn at Dunnyboe Bridge	Background	54.8384, − 7.28512	n.a	0.0005 [1]	0.0005 [1]	n.a	0.001	0.001	n.a	0.001	0.001
Lagan	River Lagan at Stranmillis Weir Station	Wastewater treatment plant	54.5685, − 5.92689	0.0057 [2][a]	0.0005 [2]	0.0005 [2]	0.0043[a]	0.001	0.001	0.007[a]	0.001	0.001
Quoile	Quoile River at Quoile Bridge	Arable	54.344700, − 5.711970	0.0039 [1][a]	0.0005 [2]	0.0005 [2]	0.0039[a]	0.001	0.001	0.0039[a]	0.001	0.001

As otherwise noted, the concentrations were taken from EIONET [13]. The LOQ of all measurements was 0.001 μg/L. Samples are reported as half LOQ if detected but below the LOQ

n.a. not available, *No access* No access permission on [13]

[a] Value taken from [14]

VMP treated dogs swimming in lakes and streams may also be a potential source for emissions to the aquatic environment [67]. A similar scenario is already described under the BPR framework for the potential release of insect repellents from human skin of swimming people [57]. Nevertheless, this is considered a sporadic and very localised incident, so emissions from this scenario are not pertinent to the monitoring data observed throughout the year under the WFD WL and nor are they pertinent to the developed model which focuses on emissions from sewage treatment plants. Spot-on VMPs include a label warning that dog owners should not allow treated dogs to go swimming for a specified time period after treatment ranging from 2 to 4 days [69, 71]. Dogs wearing collars which have a proven efficacy up to 8 months [65, 66] may swim in surface water bodies, but as concluded in the BVL assessment report (page 10, § Ecotoxicity, [70]) the environmental risk assessment performed for these products demonstrates no acute risk to the aquatic environment. This conclusion is based on the results of a tailored study simulating the condition of a dog swimming in a water body. The small volume of water (180 L) in which the dogs were bathed and the static conditions means the worst-case situations, such as during the summer months and low water flow events, are covered.

Modelled surface water concentrations

To our knowledge, it is the first time that the impact of Imidacloprid applied as spot-on products and collars on surface water concentrations is quantified via modelling. The highest Imidacloprid PECwater value of 4.81E−03 μg/L was calculated for Scenario 2, whereas the lowest value was 8.40E−04 μg/L for Scenario 1. This is in line with the maximum release fraction of e.g. up to 6.68% for spot-ons from the inventory for this emission route (Fig. 2).

In all three scenarios, the calculated Imidacloprid PEC values are at or below the ecotoxicological threshold values that have been established in the framework of different guidance documents [6, 12, 46]. The resulting risk ratios are below 1 in all cases with the exception of Scenario 2 and using the lowest and highly conservative PNECwater where the risk ratio is equal to 1. Even with a risk ratio of 1 adverse effects to surface water organisms are not expected from the use of Imidacloprid VMPs considering the conservative evaluation with the derived modelling parameters. The model outputs from the different scenarios were not summed which recognises the interconnections between the scenarios and avoids double counting. For example, the portion of imidacloprid removed from the dog coat by washing is not available for removal from the bedding.

The release fractions of each scenario were estimated including high margins of safety and thus, leading to an overestimation of emissions. This is explained for four such release fractions below:

1. The general model parameter frequency of use (F_{use}) of 13.6% reflects the highest use rate for 1 month (cats) or 2 months (dogs) a year. Other months report a use frequency being lower by a factor of 2.5, e.g. in the month of November.
2. The fractions of abrasion (F_{abr}) are set with a buffer. For dogs having been treated with spot-on products, the parameter for abrasion to their bedding has been fixed at 20% which is two times higher than study results indicate. For collars, the derived fraction is 2–3 times higher than test results.
3. A conservative approach was used for the fraction for release due to washing/bathing (F_{washing}) in Scenario 2. Immersion tests with collar wearing dogs show that only 1.64% (90th percentile) was released from the inventory during dipping. The parameter F_{washing} of 0.5 for spot-on and 0.2 for collar products provides a high margin of safety taking into account that bathing is done with shampoo and losses might be higher than during the immersion test. Furthermore, the wash-off parameter of 50% for spot-ons only considers a conservative fraction for a single washing after application and does not reflect reduced fractions available for release after multiple washings/bathings. Considering the survey data and dogs washed with shampoo, *ca.* 20% of dogs owners said they washed their dogs weekly or more frequently than this (Additional file 1: Table S2). As it is assumed 50% of the contents of spot-on are released per washing this means considering the one month protection period of the spot-on by the time of the third and subsequent washes no more imidacloprid will remain. If account is made that losses cannot in total exceed 100% of the spot-on contents applied on the same dog then the calculated PEC to PNEC ratio is only 0.4.
4. The fraction for release due to rain (F_{rain}) of 0.2 from a spot-on product used in Scenario 3 implies that all dogs being walked in the rain lose 20% of the complete applied spot-on inventory due to wash off. Even when applying spot-on products immediately prior to walking in the rain, 20% release is a large overestimate and assumes that the dog is completely wetted and high amounts of leaching water reach the paved ground. If such a high level of loss really occurred when dogs were walked in the rain, the VMPs would not have the good efficacy profiles that have been shown. This assumption is supported by the regis-

tered warnings in the product information of some spot-on products e.g. “Brief contact of the animal with water on one or two occasions between monthly treatments is unlikely to significantly reduce the efficacy of the product. However, frequent shampooing or immersion of the animal in water after treatment may reduce the efficacy of the product.” [68]. If the dog is treated days or weeks before walking the dog in the rain, considerably lower losses can be expected. For collars, the release fraction is based on the dipping test with dogs [53, 54], which was 1.64%. The rounded value F_{rain} of 0.02 was used for modelling.

Influence of substance properties on fate and behaviour

Due to the conservative approach, the total emissions of applied VMP to the surface water via STP are reflected in the presented calculation model, but not the substance-specific environmental fate during the wastewater treatment. For biocidal risk assessments, degradation and sorption processes in the STP are usually included in the emission calculations leading to lower PEC concentrations in the surface water depending on the specific nature of the substance. An adsorption coefficient normalized to organic carbon (Ka_{oc}) of 225–230 mL/g indicates adsorption of the substance to sewage sludge during treatment. This is further supported by water/sediment studies with 6.6 to 31.9% of the applied radioactivity being transferred to the sediment [44, 72]. Based on the fate parameters (data not shown, please refer to Additional file 1: Table S1), lower PECwater values can be expected assuming that a fraction of Imidacloprid is transferred to sewage sludge during wastewater treatment.

Comparison with UK monitoring results

To evaluate the contribution of VMP spot-on and collar products to surface water concentrations, Imidacloprid PEC values (8.40E−04–4.81E−03 µg/L) from the model calculations were compared to Imidacloprid concentrations in the UK surface water bodies measured at monitoring locations between 2016 and 2018 (Table 3). Our model approach followed the BPR principles for environmental risk assessment with special regard to the quantification of the emissions to surface water via STP. Consequently, the calculated PECwater values may only be compared to monitoring locations associated with a STP in urban areas. Monitoring stations in rural areas like Wensum or Ouse (Roxton) are largely characterized by agricultural land uses and were not taken into consideration for the comparison between modelling and monitoring values as these sample sites are not downstream of an STP.

Imidacloprid concentrations were measured for multiple samples taken from 29 UK monitoring locations during this period of time. For example, in 2018 results of 152 samples were reported. In 28 of these locations, imidacloprid was not detected in many samples and the highest individual concentrations observed was below 0.080 µg/L. For the other location, Somerhill, the highest average Imidacloprid concentration of 0.19 µg/L was measured in 2017, but this also corresponds to the highest individual result as only a single sample was analysed that year. In 2018 where 5 samples were taken from that site the annual average concentration of Imidacloprid was 0.14 µg/L. STP affected monitoring locations showing concentrations > 0.01 µg/L were Sincil with 0.076 µg/L (2017), Tame with 0.07 µg/L (2018), Alyn with 0.059 (2018) and Wyke with 0.044 µg/L (2016) (Table 3). However, lower average concentrations < 0.01 µg/L were detected at other urban STP characterized locations like Clyde (0.009 µg/L, 2017) or Lagan (0.0057 µg/L, 2016). It was also observed that Imidacloprid was detected in monitoring locations characterized as urban but without connection to an STP, e.g. Irwell (0.023 µg/L, 2018) and Chelt (0.015 µg/L, 2016). This indicates Imidacloprid emissions in urban areas without STP effluent discharge cannot be solely attributed to the use of VMP spot-on and collar products as reflected by the three scenarios. Other point sources near rivers or run-off must also contribute to emissions of Imidacloprid to the surface water. In comparison, the highest PEC value of 4.81E−03 µg/L (Scenario 2) is ca. 2.5% of the highest monitoring value detected in wastewater treatment plant affected rivers in the UK. Hence, the use of Imidacloprid as a VMP for companion animals can only explain a very low portion of the measured surface water concentrations.

Comparison with other European study results

Several studies have been published showing Imidacloprid residues from various applications in surface water in other European countries [73–75]. Casado et al. [73] screened various waterways in European countries for the occurrence of veterinary drugs and pesticides including Imidacloprid. The focus was set on small waterways with a typical land use pattern. These catchments were either associated with a high density of livestock to monitor veterinary drugs or connected to considerable arable production areas to monitor for pesticides. The sampling of streams receiving urban effluents or having a STP upstream was avoided. Two rivers in the UK showed Imidacloprid concentrations of 0.007 and 0.014 µg/L. In total, Imidacloprid was detected in 86% of the 29 European sampling locations (LOQ = 0.0025 µg/L). The highest concentration was measured in a river in Spain, containing 0.047 µg/L. Further residues of pesticides which are no longer approved and applied EU wide, were detected. The authors attributed those residues to runoff and leaching out of soils and sediments originating from the historic use of the substances. This residual leaching behaviour may be also relevant for Imidacloprid indicated by its affinity for adsorption to sediment and a low degradation in soils [44, 72]). Rico et al. [74] analysed contaminants of concern in the upper Tagus river basin in central Spain. Imidacloprid has been measured up to 0.34 µg/L using a passive sampling method, while direct sampling resulted in concentrations up to 0.021 µg/L. The high frequency of detection could indicate that some agricultural activity is present in all sub-basins of the studied area, but the agricultural impact may differ for each sub-basin. Tsaboula et al. [75] analysed water samples from the Pinios River Basin in Greece with mean and maximum concentrations of 0.034 µg/L and 0.306 µg/L, respectively.

In comparison to the results from the literature, it can be observed that our calculation model predicts surface water concentrations which are similar to much lower (more than one magnitude) than the concentration observed in the monitoring data from sampling sites downstream of STPs. It can be assumed that VMP spot-on and collar products may contribute to Imidacloprid surface water concentrations, but only to a minor extent. Furthermore, the calculated surface water concentrations are much lower than the monitored Imidacloprid concentrations across Europe. Since UK specific sales and use data was used for input parameter derivation the results of the modelling are only comparable to other countries to a certain extent. The number of households in the UK treating pets with collars or spot-on products are considered for the parameter $F_{\text{houses,treating}}$. Higher (lower) numbers would result in higher (lower) calculated surface water concentrations. The same applies to the annual amount of Imidacloprid being released from all cats and dogs to the same STP $Q_{\text{ai,dogs,cats}}$. For the derivation of the parameters F_{use}, F_{sim} and F_{STP}, results from a survey among cat and dog owner UK were used. As the UK is one of the European countries with the highest use volumes of these products and also one of the countries with the highest density of dogs (compared to land mass) it is not expected that higher PECs would be calculated in other European countries [76–79].

As discussed above, Imidacloprid concentrations in the UK surface waters cannot be attributed to a specific end-use of the compound but may result from various applications. We, therefore, analysed the catchment environment of exemplary UK sampling stations with the evidence of Imidacloprid concentrations to examine potential emissions sources.

The WL includes a range of monitoring stations to reflect various surrounding land uses according to [59]. The authors state, that watercourses are almost always influenced by various land uses. For example, smaller, local STPs may affect measurements on monitoring stations in agricultural areas. In contrast, urban monitoring stations will often be influenced by upstream agricultural land use. Since Imidacloprid is used as BP, VMP and PPP, emissions to wastewater are possible from various sources. Next to the authorized applications, Imidacloprid may also be discharged to wastewater due to pollution incidents from washing farm machinery, inappropriate disposal of insecticide, disposal of potted plants or flooding events [59].

The highest Imidacloprid concentrations were measured at Somerhill monitoring station located downstream of a small STP with a capacity of approximately 28,000 population equivalent [64]. Somerhill Stream is a very small stream with a length of ca. 8 km and a catchment of only 18 km^2 indicating a low dilution factor of potential emitted chemical substances [60]. This STP catchment is characterized by several recreational areas like parks and garden centres. These areas and specific locations may act as sources for potential Imidacloprid emissions due to previously treated plants [14]. However, it is not possible to quantify the extent of emissions. The same applies to the monitoring stations Wyke, Sincil and Tame characterized by larger STPs and catchment areas with many recreational areas and garden centres. In the catchment of the station Lagan, parks and golf courses are located. Golf course turf is known to have been treated with Imidacloprid in the past [14, 21]. Furthermore, an impact on surface water concentrations from flooding events at the Somerhill location cannot be excluded [80, 81]. In general, every discussed factor may contribute to the measured Imidacloprid concentrations of up to 0.19 µg/L at Somerhill monitoring station (Table 3) and the general high values for STP affected surface water bodies. However, it is not possible to identify the major single source of emission. An impact of VMP uses cannot be excluded. However, the performed worst-case calculations indicate no adverse effects on surface water organisms by the modelled surface water concentrations.

Limitation of the model and outlook

We developed the model in accordance with the BPR framework and used conservative input parameters. This approach may lead to an overestimation of the PECs especially when considering that degradation of Imidacloprid in environmental compartments such as surface water and sewer are not taken into account. However, higher tier modelling tools as used for PPP authorization such as landscape-scale modelling or more dimensional simulations are available and would result in more realistic modelled Imidacloprid concentrations. However, such sophisticated modelling is not warranted as a relevant threshold are not exceeded. For the quantification of the actual VMP impact on surface water concentrations, a monitoring campaign may be preferable but is technically not feasible due to the wide dispersive applications. Another difficult aspect of monitoring is the distinction between the identified VMP emission scenarios and their concurrent emission patterns.

The model for the three scenarios could be applied to other European countries by varying the input parameters subject to the availability of the necessary survey data. This would allow the validity of the assumption, that similar or lower PECs would be expected compared to the UK, to be checked.

In addition to the three major emission paths evaluated by the authors, release from hand/cloth washing after the stroking of the pets and hands wiping on clothes, could be further investigated and a model built as one separate scenario to estimate potential chronic aquatic exposure to check the validity of the assumption that this is not a significant emission path.

Conclusions

We developed a model comprised of three potential continuous emission scenarios to predict Imidacloprid surface water concentrations stemming from sewage treatment plant effluent as a consequence of the use of VMPs containing Imidacloprid in the UK. The calculated surface water concentrations did not exceed established ecotoxicological threshold values indicating acceptable safety for aquatic invertebrate organisms. The calculated concentrations were also found to be much lower than the UK monitoring data for river water. For example, the calculated concentration from the bathing/washing of dogs was < 3% of the highest levels of Imidacloprid measured in surface waters.

The model results have shown a low exposure to the aquatic environment from the use of imidacloprid containing veterinary medicines which deliver important benefits to animals and people. This confirms that the assumption in the guidelines on environmental risk assessment for companion animal products that exposure is low is correct. According to these findings, the current approach to the EU Environmental Risk Assessment of antiparasitic VMPs applied topically to treat pets and to protect them from parasites remains appropriate.

Supplementary information

Supplementary information accompanies this paper at https://doi.org/10.1186/s12302-020-00424-4.

Additional file 1. Supplementary information on Imidacloprid parameters, VMP studies and market survey.

Abbreviations

AF: Assessment factor; BPR: Biocidal Products Regulation; BP: Biocidal product; EC: European Commission; ECHA: European Chemicals Agency; EIONET: European Environment Information and Observation Network; EPM: Equilibrium partitioning method; EQS: Environmental Quality Standard; EU: European Union; Ka_{oc}: Adsorption coefficient normalised to organic carbon in soils; LOQ: Limit of quantification; PECwater: Predicted environmental concentration in surface water; PNECwater: Predicted no effect concentration in surface water; PPP: Plant protection product; STP: Sewage treatment plant; UK: United Kingdom; VMP: Veterinary medicinal product; WL: Watch List; WFD: Water Framework Directive.

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Authors' contributions

The aquatic risk assessment was performed in full by MA and each step was discussed with all authors. All authors reviewed the manuscript before submission. All authors read and approved the final manuscript.

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Availability of data and materials

The datasets used and analysed during the current study are available from the corresponding author on reasonable request.

Ethics approval and consent to participate

Not applicable.

Consent for publication

Not applicable.

Competing interests

M. Anthe, J. Achtenhagen and Martina Arenz-Leufen work as consultant for Bayer Animal Health.

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