The overland transport of veterinary antibiotics: a synthesis

Caroline Bailey, Holger Schüttrumpf and Roy M. Frings

Abstract

Veterinary Antibiotics (VAs) are emerging agricultural contaminants. They are applied to agricultural fields in excrement-based fertilizers around the world. Whilst VA groundwater and plant contamination has been researched over the past decades, the overland transport of VAs in runoff water and the associated soil erosion has received significantly less global research attention. The overland transport of VAs from fields may result in the contamination of surface water systems (water and sediment) with potentially negative consequences for ecosystems and humans.

A synthesis of five related studies is presented, which were conducted to improve understanding of the overland transport of VAs. Where applicable, the study area is the country of Germany. The studies include a literature review, sampling schemes, laboratory experiments and the development of a numerical model; designed to estimate VA overland transport flux across the study area. The achievements and limitations of the presented work are addressed and recommendations for further research are given.

The presented work is a synthesis of the doctoral thesis of the corresponding author Caroline Bailey, entitled “The overland transport of veterinary antibiotics”. The thesis is available in digital form upon request.

1 Introduction

Hundreds of thousands of tons of antibiotics are used globally in livestock medicine every year (Wise, 2002). Veterinary antibiotics (VAs) are used to treat infections caused by bacteria, parasites and fungi (WHO, 2014). When VAs are administered to animals, 50–90% of their mass is not absorbed into the body and is consequently found in animal excrement (Sarmah et al., 2006, and references therein). By applying animal excrement to fields as fertilizer, VAs are introduced to soil and pore liquid. They may consequently be transported to groundwater via infiltration (Hamscher et al., 2005), plants via evapotranspiration (Boxall et al., 2006) or surface water systems (water and sediment) via overland transport (Davis et al., 2006) from where they may be transferred to drinking water (Ye et al., 2007), flora and fauna (Li et al., 2012). Via drinking water and the food chain, VAs may be ingested by humans. This is a health risk due to the consequent promotion of VA-resistance formation in human bodies (Sarmah et al., 2006, and references therein).

The agricultural VA transport route that has been most highly scrutinised around the world is the vertical transport of VAs from agricultural soils to groundwater (a drinking water source) via infiltrating precipitation water (Hamscher et al., 2005). The VA transport route that has received significantly less global attention is the overland transport route: the transport of VAs from agricultural fields to surface water systems in surface runoff and eroded soil particles (Fig. 1).

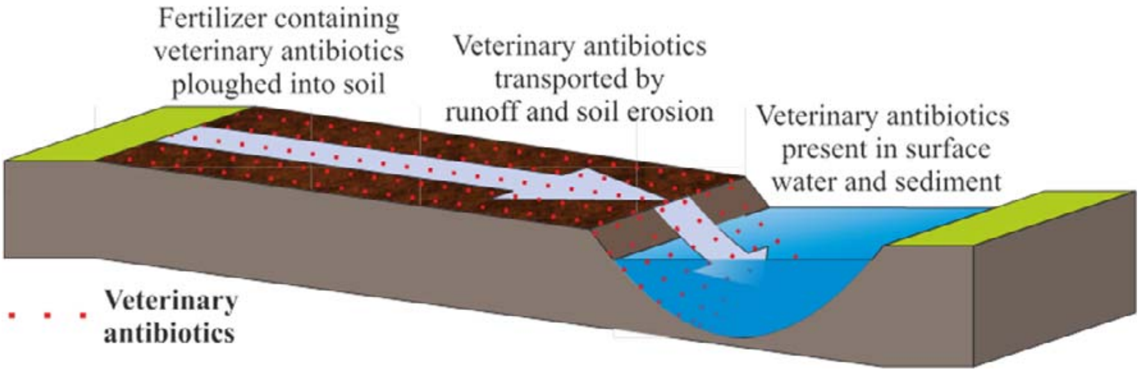


Fig. 1: The overland transport of veterinary antibiotics

Consequentially, research has been conducted (funded by the German Federal Ministry for Education and Research, BMBF) with the objective of predicting the overland transport of veterinary antibiotics. This was achieved by conducting a series of related research studies. These studies enabled the conceptualisation of the whole VA overland journey as a series of connected steps; starting with the application of VAs to fields in fertilizer, ending with VA residence in surface water systems and accounting for VA behaviour in host materials along the route. The chosen study area was Germany.

This aim of this paper is to present a synthesis of the above-mentioned research; a more detailed version is available from the authors upon request. Firstly, a summary of different research studies is presented, in which the aims and relevance of each study and the knowledge that was gained as a result of each one are highlighted. The connections between the separate studies are stressed and the conclusions which can be gathered from the compiled studies are stated. The limitations of the presented research are subsequently discussed and recommendations for future research are given.

2 Summary and synthesis of presented work

2.1 Structure

The thesis was divided into five interconnected studies, Studies 1–5 (Fig. 2).

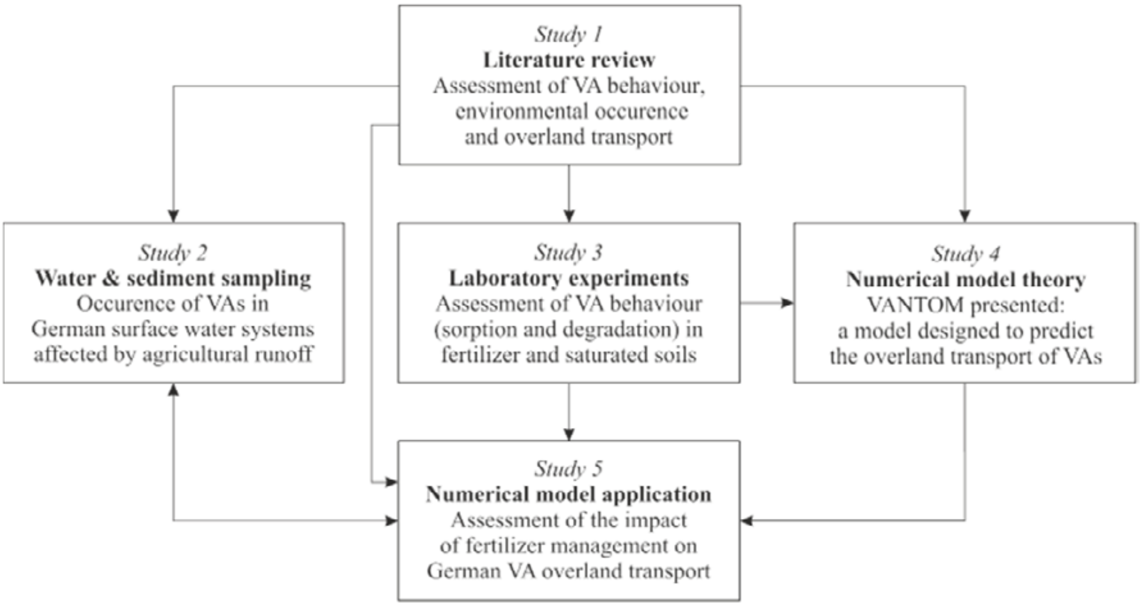


Fig. 2: Diagrammatic conception of research structure: five related studies

(1) A **literature review** was conducted to determine and critically review the current state of global research into the overland transport of VAs. (2) **Water and sediment sampling** schemes were conducted within Germany to assess VA surface water system contamination within the chosen study area. (3) **Laboratory experiments** were conducted to determine the solid-liquid partitioning and degradation of VAs in fertilizer and soil. (4) **Numerical model theory.** The theory of the Veterinary Antibiotic Transport Model (VANTOM) was presented; a model was designed to simulate the masses of VAs which are applied, transported to surface water systems and accumulated of agricultural land across a study area over a time period. (5) **Numerical model application.** The influence of fertilizer management on VA overland transport in Germany was investigated using VANTOM. Rates of runoff and soil erosion (VA transporting agents) across Germany were provided by coupling VANTOM with the Pan European Soil Erosion Risk Assessment (PESERA), an existing process model.

2.2 Literature review (Study 1)

The aim was to determine and critically assess the current state of scientific knowledge surrounding the overland transport of VAs from the sulfonamide and tetracycline groups. Gaps in current knowledge and requirements for further research were identified. Data was gathered from relevant peer-reviewed journal papers, textbooks and legislature. Topics of interest were: the behaviour of VAs in host materials (fertilizer and soil), the detected concentrations of VAs in different environmental compartments (fertilizer, soil and surface water systems) and the mechanisms which govern the overland transport of VAs (surface runoff and soil erosion).

The study discovered that the majority of research in this field so far had been aimed at the detection of VAs in fertilizers and soils and their behaviour therein, although the lack of some behavioural constants in published literature (sorption coefficients and degradation constants) prevented clear comprehension of the transfer of VA masses from fertilizers to soils. The overland transport of VAs and the consequential contamination of the environment were found to be under-researched. A small number of studies from around the world were found that confirmed the overland transport of VAs (in experimental conditions) and the occurrence of VAs in surface water systems (water and sediment) in areas specifically affected by runoff from agricultural areas. Antibiotics were also found to have been detected in human drinking water and food sources (flora and fauna), although their source (humans or veterinary medicine) is unclear.

In general, it was found that the overland journey of VAs from fertilizers to surface water systems had never been conceptualised as a series of connected steps. It was recommended that the journey should be simulated over a study area (in which VA contamination in surface water systems was suspected to be prevalent) by expanding a physically-based soil erosion model to account for the occurrence and behaviour of VAs in masses of soil and water that were transported overland. This would allow the masses of transported VAs to be assessed with spatial and temporal variation, whilst taking into account the major factors that influence the overland transport of material (climate, soil type, vegetation and topography).

The following presented studies each contribute to completing this conceptualisation of the overland transport of VAs across the study area of Germany.

2.3 Water and sediment sampling (Study 2)

This study has been published in full by Bailey et al. (2015).

The literature review (Study 1) identified a global lack of surface water sampling schemes in areas that were specifically affected by runoff from agricultural land. The aim of this study was to assess if VAs were present in German surface water systems (in both water and sediment) following their overland transport from agricultural fields in runoff and soil erosion. This was the first study conducted in Germany in which the analysis of sediment samples from areas of potential VA contamination was conducted.

Three water and sediment sampling schemes were conducted in Germany to examine the effects of (1) season, (2) heavy rainfall and (3) high veterinary antibiotic usage. During the three schemes, the antibiotics sulfapyridine, sulfamethoxazole, sulfathiazole, sulfamethazine and tetracycline were detected in all three schemes in trace quantities, which was the first time that veterinary antibiotics had been detected in German sediment. In particular, the presence of the VA tetracycline in water and sediment taken from irrigation ditches in an agricultural area of high veterinary antibiotic usage offered proof that the overland transport of veterinary antibiotics was occurring in Germany and that further research into the involved processes was justified in this study area.

2.4 Laboratory Experiments (Study 3)

The literature review (Study 1) identified a lack of research into the solid-liquid partitioning of VAs in fertilizer and the separate degradation of VAs in the solid and liquid phases of a host material. The transfer of VA masses from fertilizer to soil was therefore considered to be difficult to conceptualise.

To do so and hence to replicate the journey that VAs follow between the animal stall and environment, two experiments were conducted to examine the behaviour of the VAs sulfadiazine, sulfamethazine, sulfamethoxazole and tetracycline as they were transferred from fertilizer to soil. The solid-liquid partitioning of VAs in different densities of cow excrement, fertilized sandy soil and fertilized clayey soil was observed over 30 days (sorption coefficients, K_d [kg kg^{-1}] were calculated). The degradation constants of VAs in the solid and liquid phases of each host material were also observed over 30 days (degradation constants of VAs in solid form, k_s [day^{-1}], and liquid form k_l [day^{-1}] were calculated).

In excrement, the majority of the VA mass was found in the liquid phase. In the saturated soils, the majority was found in the solid phase (Fig. 3). Sorption coefficients were not influenced by excrement solid content and were higher in clayey than in sandy soils. Tetracycline exhibited stronger sorption to solids than the analysed sulfonamides. Sulfamethoxazole degraded in the cow excrement within 30 days, indicating that the introduction of this VA to fields is unlikely. No degradation of sulfadiazine, sulfamethazine or tetracycline was observed in soil solids, indicating that their accumulation on fields and transport via soil erosion is likely. The degradation of all VAs was faster in sandy soil liquid than clayey soil liquid. Figure 3 indicates the fate of the initial mass of sulfadiazine and tetracycline found in cow excrement, according to the results of the experiments. In both cases, the majority of the VAs can be assumed to sorb to solid particles and hence either persist on agricultural fields or be transported in solid form (via soil erosion). A greater mass of sulfadiazine may be transported in liquid form than tetracycline, due to the generally lower sorption of sulfonamides to solid particles.

The trends identified in this study allowed the transfer of VA masses from fertilizer to soil to be understood clearly for the first time and for these steps of the VA overland journey to be modelled (Chapters 5 and 6), using the calculated behavioural constants as input data.

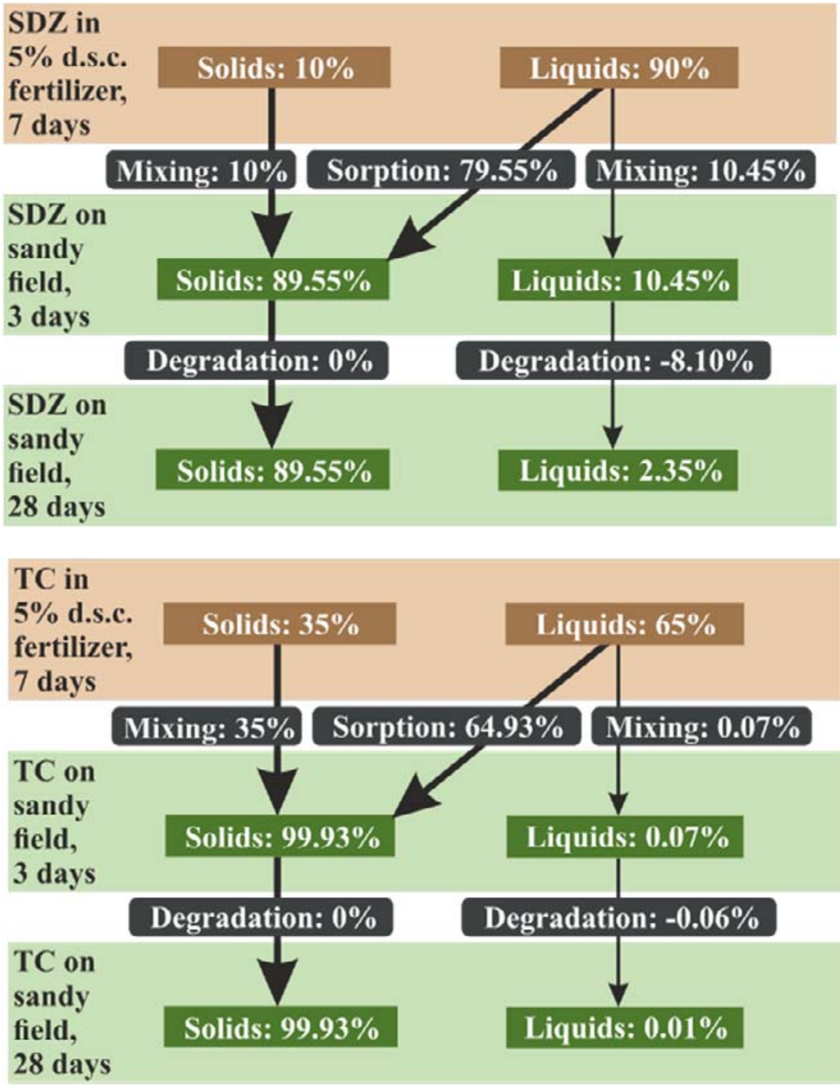
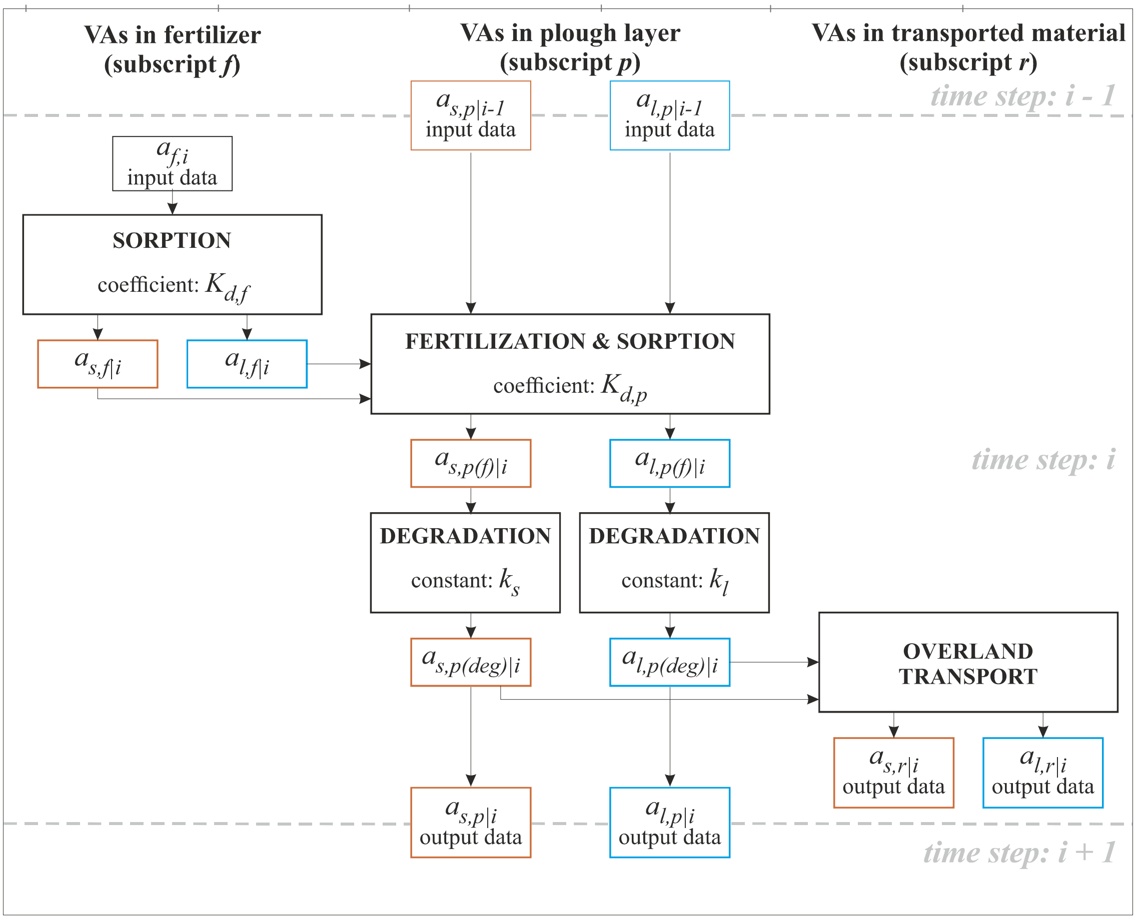


Fig. 3: The sulfadiazine (SDZ) and tetracycline (TC) journeys (approximate values). d.s.c. = dry solid content

2.5 Numerical Model Theory (Study 4)

The literature review (Study 1) identified the need to conceptualise the overland journey of VAs from fertilizers to surface water systems as a series of connected steps. The Veterinary Antibiotic Transport Model (VANTOM) was developed, with the aim of predicting the fate of VAs that are applied to fields in fertilizer, be it transport to surface water systems, accumulation on fields or degradation (Fig. 4). This was achieved by considering VA sorption in both fertilizers and soils as well as degradation rates, as determined in the laboratory experiments (Study 3).



VAs in solid form = subscript *s*; VAs in liquid form = subscript *l*
VAs after fertilization = subscript *(f)*; VAs after degradation = subscript *(deg)*

Fig. 4: Conceptualisation of key events and VA behaviour in the plough layer in time step i

The resulting masses of VAs that were calculated to be in soil solid and soil liquid were considered to be liable to overland transport if present in the top millimetres of the field. The transfer of VAs from fields to surface water systems (via overland transport) was modelled by coupling VANTOM with an existing model that is capable of calculating rates of runoff and soil erosion (the VA transporting agents) over the desired study area. The process model PESERA (Pan European Soil Erosion Risk Assessment) (Kirkby et al., 2008) was chosen for this task due to its aptitude to large study areas, such as Germany.

VANTOM is applicable to small or large study domains, for short or long study periods. VANTOM calculates a VA mass budget within each time step (Fig. 4), which accounts for the addition of VAs to fields via fertilizer application and their subtraction via degradation and transportation in runoff water and eroded soil. The solid-liquid partitioning of VAs in both fertilizer and soil is considered. The downwards transport of VAs due to infiltration, the upwards transport of VAs due to evaporation or uptake through plants, and the lateral transport of VAs due to groundwater flow in the unsaturated layer are not modelled.

A case study was presented in which the fate of the VAs sulfamethazine and tetracycline was examined over one year (in time steps of one month), following their application to agricultural fields in fertilizer across Germany in the month of March. Behavioural constants (sorption coefficients and degradation constants) were taken from the results of Study 3. When fertilizer was applied to soil, the majority of VAs sorbed to the soil solid, where they persisted (due to the lack degradation in soil solid) and from where they were transported overland in solid form. VA overland transport was found to take place in trace quantities across Germany, primarily in solid form, with peak transport rates occurring in the basins of the rivers Weser, Elbe and Danube (Fig. 5). This correlates well with the results of the water and sediment sampling study (Study 2) in which tetracycline was detected in sediment in the basin of the river Weser. The average concentrations of sulfamethazine and tetracycline that were calculated to be in fertilizer, soil and surface water systems by VANTOM were found to correlate with reasonable accuracy to concentrations of sulfamethazine and tetracycline that were detected in the sampling schemes discussed in the literature review (Study 1).

This was the first time that the entire VA overland journey was conceptualised over a study area. Although specific results should be treated with caution due to the generalisation of input data, assumptions in modelled processes, low temporal and spatial discretization, VANTOM can be considered a useful tool for indicating VA contamination hotspots across Germany.

2.6 Numerical Model Application (Study 5)

The aim of this study was to investigate the effects of different fertilizer management variables on the masses of VAs which contaminate agricultural fields and the VA masses which are subsequently transported overland across Germany. The assessed fertilizer management variables were (1) fertilizer type: cow excrement, pig excrement or biogas digestate, (2) fertilizer application choice: 45 m^3 $hectare^{-1}$ applied once per year (March) or 22.5 m^3 $hectare^{-1}$ applied twice per year (March and June), and (3) the depth to which fertilizer is ploughed into fields: 30 cm or 15 cm. By combining these variables to observe their effects on the overland transport of (a) the sulfonamide group and (b) the tetracycline group, 24 different scenarios were created.

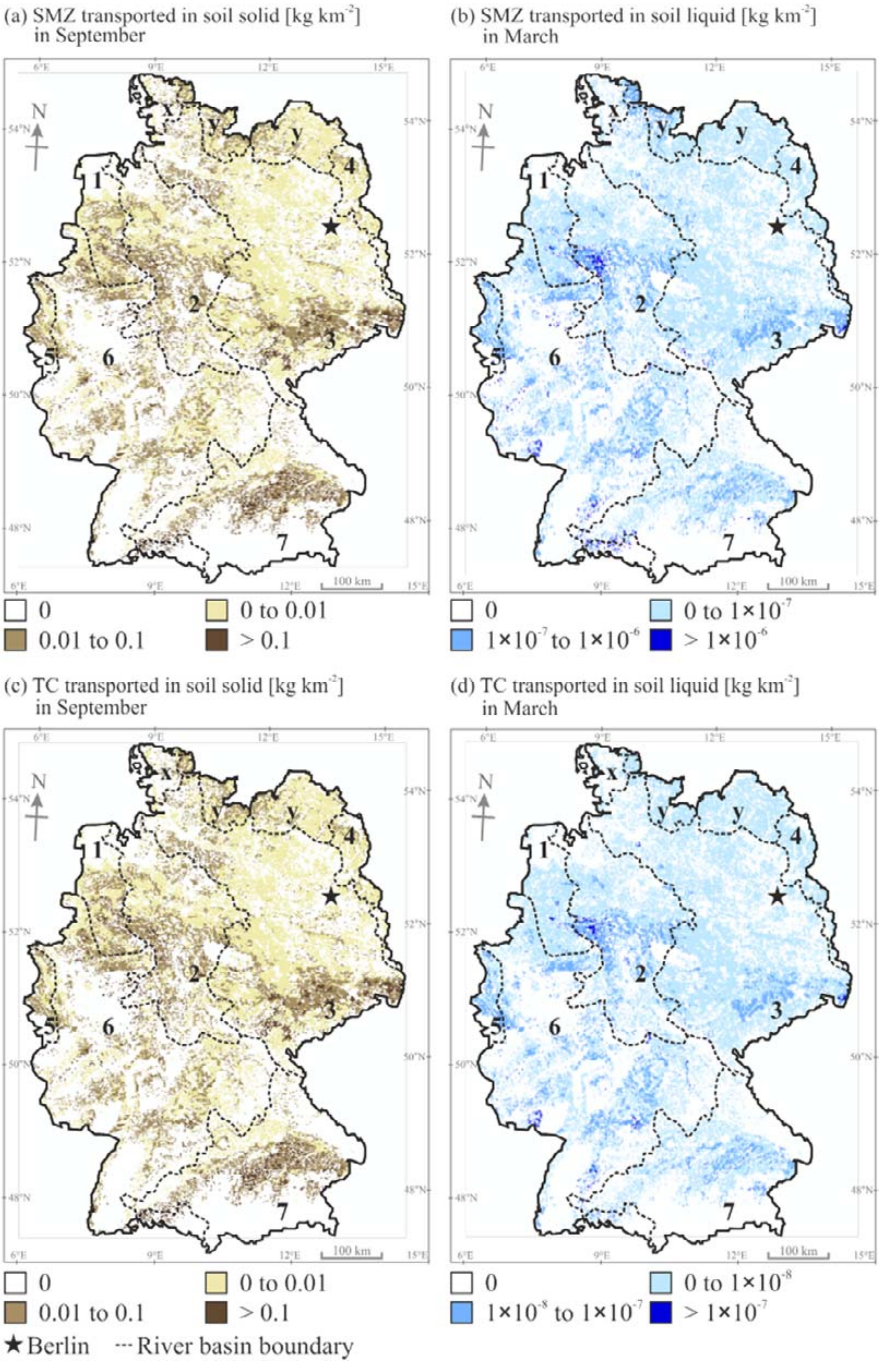


Fig. 5: Maximum overland transport. Masses of SMZ [kg km-2] transported in (a) soil solid in September, (b) soil liquid in March; masses of TC [kg km-2] transported in (c) soil solid in September,(d) soil liquid in March, in Germany's major river basins: (1) Ems, (2) Weser, (3) Elbe, (4) Oder, (5) Meuse, (6) Rhine, (7) Danube. Areas marked (x) and (y) drain into the North Sea and Baltic Seas respectively.

The literature review (Study 1), identified a lack of published data regarding the temporal variation of VAs in different fertilizers. To acquire this data, samples of dairy cow and pig excrement were collected monthly from German farms and analysed for their VA concentrations. Temporal distribution data of VAs in biogas plant digestate fertilizer was taken from published literature (Spielmeyer et al., 2015). The VAs sulfadimethoxine, sulfadiazine, sulfamethazine, sulfathiazole, chlortetracycline, oxytetracycline and tetracycline were detected in the analysed German fertilizers. Concentrations were highest in birthing season or in periods of bad weather. The observed temporal trends of VAs mass in each fertilizer type were combined with data released from the German government (BVL, 2014) regarding the spatial variation of VA usage across Germany, making it possible to estimate the mass of VAs in each fertilizer type in any region of Germany for any month of the year. Although this data is acknowledged to be generalised, it is the first time that the temporal trends of VAs in different fertilizers have been extrapolated across a country, to aid the conceptualisation of where and when large VA masses are applied to fields.

The model VANTOM (Study 4) was again coupled with the existing process model PESERA and used to predict the masses of VAs that were transported overland across Germany over one year as a result of the 24 fertilizer management scenarios. VA behavioural constants (sorption coefficients and degradation constants) were again taken from the results of Study 3. Results showed that maximum VA overland transport occurred when all fertilizer types were ploughed to a depth of 15 cm and that higher rates of overland transport in liquid form occurred at different times of year depending on the VA mass in fertilizer when it was applied. Peak transport rates of VAs in solid form took place in September, due to increased rates of soil erosion in this month across Germany. The majority of VAs applied in fertilizer were found to accumulate in soil solid due to the sorption of VAs to solid particles and the consequent lack of degradation in that state. For this reason, greater masses of VAs were both accumulated and transported in solid form than liquid form.

VANTOM was finally used to run scenarios for six consecutive years in areas of (1) sandy soil (Fig. 6) and (2) clayey soil (Fig. 7) in order to observe long term trends, which indicated that VAs accumulate in soil solid at decreasing rates per year and in soil liquid at increasing rates per year due to constant solid-liquid partitioning coefficients. The addition of fluid to contaminated soil increased the mass of VAs in soil liquid due to the desorption of VAs from soil solid.

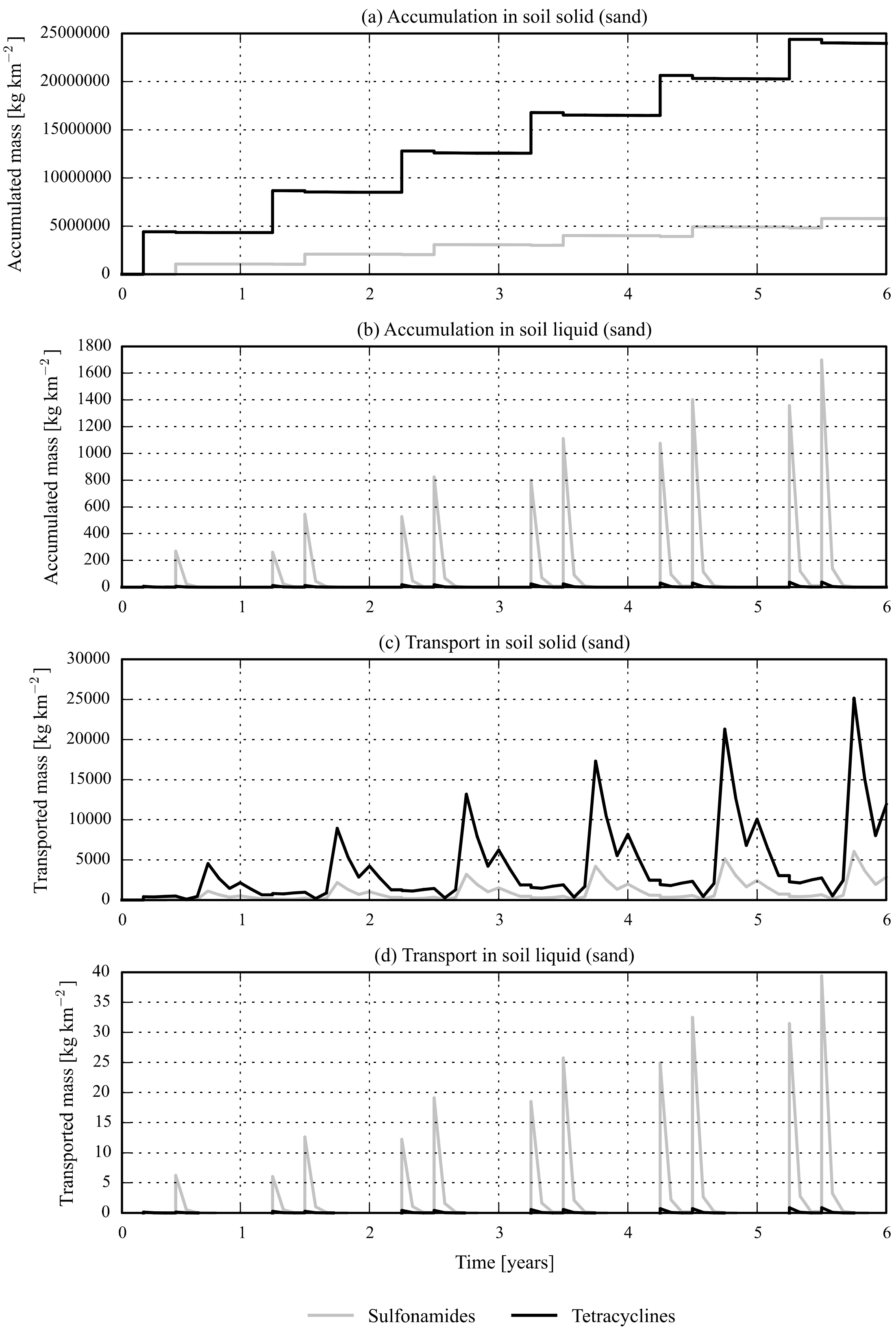


Fig. 6: **Long term effects of applying cow excrement to sandy fields bi-annually (plough depth 15 cm) on the accumulation in solid form (a) and liquid form (b) plus the overland transport in solid form (c) and liquid form (d) of the sulfonamide and tetracycline groups**

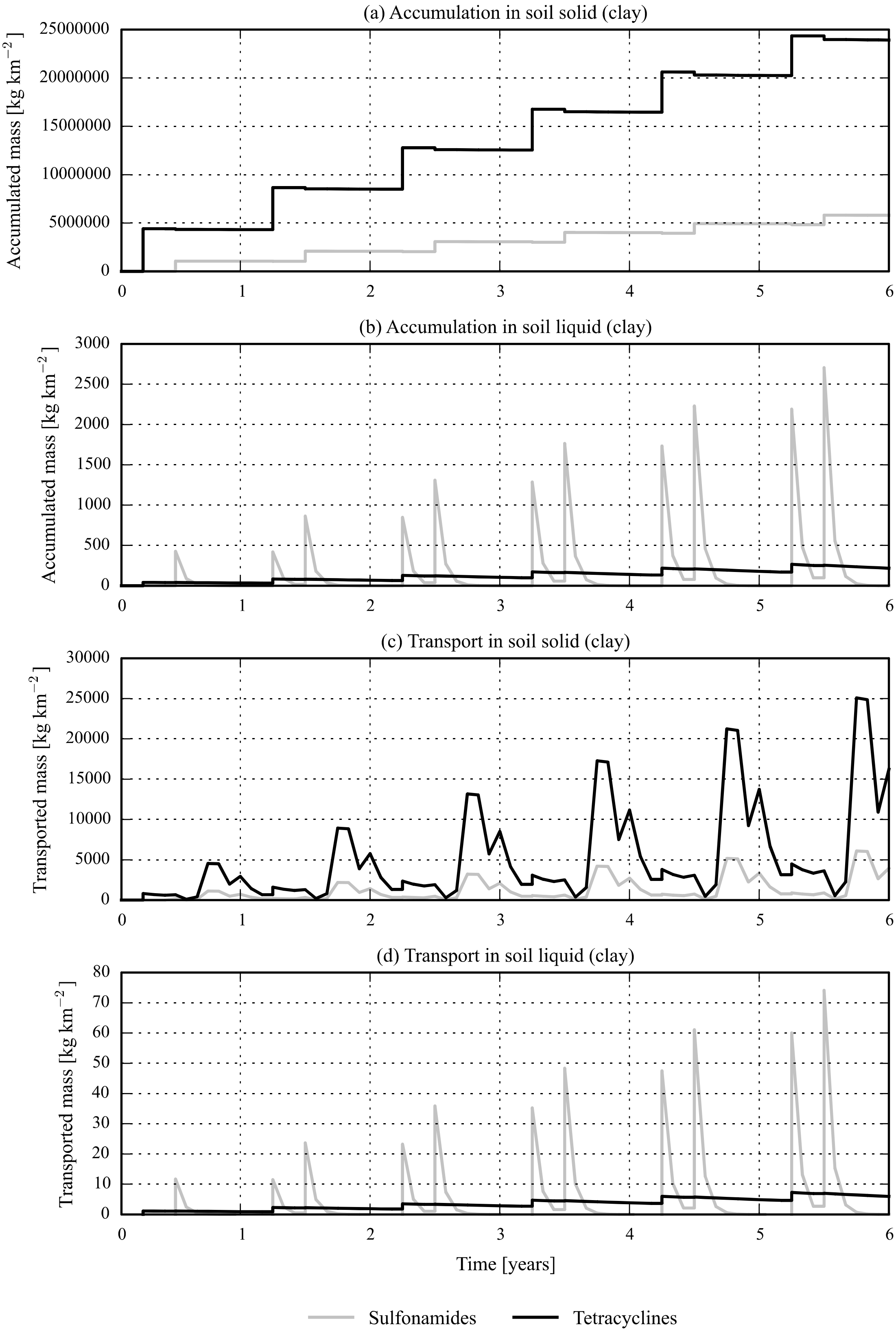


Fig. 7: Long term effects of applying cow excrement to clayey fields bi-annually (plough depth 15 cm) on the accumulation in solid form (a) and liquid form (b) plus the overland transport in solid form (c) and liquid form (d) of the sulfonamide and tetracycline groups

3 Research Achievements

For the first time, the overland transport of VAs across a study area has been modelled: the objective of the thesis has therefore been achieved. Research has been conducted into the environmental contamination of VAs over the past twenty years, but studies were generally either concerned with VA behaviour in just one compartment (fertilizer or soil) which were difficult to compare to others due to the inconsistency of control parameters (such as the organic content and pH of host materials, which affects the solid-liquid partitioning of VAs), or they were concerned with VA detection in different compartments without considering how VAs were practically transported from one to the next.

Whilst the detection of VAs in different environmental compartments around the world has increased and generalised notions of transportation and behavioural trends have become accepted, this is the first time that the whole VA overland journey has been conceptualised as a series of connected steps; starting with the application of VAs to fields in fertilizer, ending with VA residence in surface water systems and accounting for VA behaviour along the journey (the solid-liquid partitioning of VAs in different host materials and separate degradation rates for VAs present in solid and liquid form). Implemented input data are generalised but relevant to the study area of Germany; results are also generalised but present useful trends and correlate (with reasonable accuracy) with the findings of published sampling schemes.

The compilation of research studies presented in this thesis, which ultimately lead to the execution of numerical model scenario analyses to determine the influence of fertilizer management techniques on the overland transport of VAs across Germany, is considered by the authors to represent a comprehensive and practical advancement in the current appreciation of VA overland transport. Areas and months of high VA transport in Germany have been identified, which will allow field research to become more focussed in the future. The visual aspects of the studies will help to communicate of the scale of the problem to concerned parties, which may help lead to the development of contaminant mitigation methods in the future.

The main trend which has been identified as a result of the above research, and which was not found to be regularly discussed in published literature, was that the majority of VAs which are transported overland are transported in solid form (attached to eroded soil particles). This is due to the sorption of VAs to soil solids on agricultural fields, their accumulation thereon and their consequential transport therefrom. This identified trend is supported by the detection of VAs in the sediment of agricultural drainage ditches in Study 2 and the high K_d values and low k_s values of VAs in soils that were calculated in Study 3.

Published research regarding the transport of VAs in the environment has so far mainly focussed on the transport of VAs in liquid form. This thesis stresses that only a very small percentage of the mass of VAs administered to animals is present in liquid form on the field following its application in fertilizer (Study 3) and that the majority of that small percentage will degrade within a few months (Studies 4 and 5). The addition of liquid to VA contaminated soil (be it from rain or the application of non-contaminated liquid fertilizer) was found to cause the desorption of small masses of VAs from soil solid which were liable to transportation in liquid form until their subsequent complete degradation.

4 Research Limitations

The trends that are presented in this thesis are considered to be generally valid and applicable around the world. However, due to the generalisations and assumptions that were made in the process of calculating VAs masses that were transported overland (in this case across Germany), specific calculated results must be treated with caution.

Perhaps the most controversial generalisation that was made was the use of the VA sorption coefficients and degradation constants that were calculated in Study 3 as input data for VANTOM, and which were consequently applied across Germany (Studies 4 and 5). The behavioural constants were calculated in Study 3 following the 30 day observation of VAs in firstly cow excrement and secondly saturated soils (sandy and clayey) which had been fertilized with VA-contaminated cow excrement. The use of the resultant behavioural coefficients is controversial as the experiments were only conducted over 30 days, yet the behavioural constants they produced have been used in VANTOM to replicate VA behaviour in soils for up to six consecutive years; it is probable that the long term predictions of VA occurrence in soils (Study 5) are (at least partially) incorrect. This is particularly relevant to the degradation of VAs in soil solid (which was assumed to be equal to zero for all VAs), meaning that extreme accumulation of VAs in soil solid was observed per year, also influencing the masses of VAs which were transported (in both solid and liquid form). These behavioural constants were used due to a lack of appropriate alternative (for example, separate degradation constants for VAs in solid and liquid form were not found in published studies), but the acquisition of long-term behavioural constants is recommended for future uses of VANTOM.

Input data provided by PESERA (the masses of runoff and eroded soil which are transported overland, acting as VA carrying agents) is also inaccurate (Studies 4 and 5). It was declared by its developers (Van Rompaey et al., 2003) to have an error margin of up to a factor of four, which will affect the accuracy of transported VAs by up to a factor of four. Data calculated by PESERA can be improved by refining the discretization of PESERA input data; for example, gathering data on a grid with cell areas of 250 m^2 rather than 1 km^2. Whilst PESERA was an appropriate choice for a study area as large as Germany, if a smaller study area is considered in the future, the use of a more accurate soil erosion process model should also be considered.

Input data regarding the spatial and temporal occurrence of VAs in different fertilizers (Study 5) was also strongly generalised: temporal trends obtained from sampling fertilizer types from single farms were extrapolated across a whole country. This measure was again taken due to the lack of alternatives: fertilizer samples studies (which consider the temporal variance in VA occurrence) have not been conducted for different fertilizer types across the study area of Germany. Similar problems arose when judging the accuracy of VANTOM results (Study 4): no soil or surface water system sampling schemes which consider the temporal variance in VA occurrence have been conducted across Germany. In the future, if a smaller study area is investigated, then fertilizer, soil and surface water systems samples should be analysed across the study area (with temporal variation) in order to provide better input data and validation data for future VANTOM simulations.

Aside from the quality of input data, VANTOM offers approximate results due to assumptions that are made in the processes that are modelled. For example, because fertilizer events and runoff events are separated by the fixed duration of one or more time steps, VA mass reductions due to degradation, which are time dependent, are affected. For higher accuracy, a sub-time step system could be introduced, so that fertilizer and runoff events can be flexibly separated by any temporal interval and the corresponding degradation losses calculated appropriately. The liquid degradation constants for sulfamethazine (calculated in Study 3, implemented in Studies 4 and 5) indicated that total degradation occurred within two to four months of VA-contaminated fertilizer application to fields. Considering the approximate nature of all implemented VANTOM input data, the finer accuracy which would be provided by using a sub-time step (i.e. in which days of the month VAs exist and are transportable in soil liquid) would not significantly alter the usefulness of the results. However, if a VA with higher degradation rates were modelled and more accurate results were required, either a sub-time step or shorter time steps (i.e. one week or one day) could be employed, in conjunction with more accurate input data.

Another simplification of VANTOM is that it does not account for the downwards transport of VAs due to infiltration, the upwards transport of VAs due to evaporation or uptake through plants, nor the lateral transport of VAs due to groundwater flow in the unsaturated layer. Again, based on the very small quantities of VAs that have been calculated to be present in soil liquid in Studies 4 and 5, modelling these processes will not significantly alter generalised results and is therefore not necessary unless high accuracy is desired.

5 Recommendations and closing remarks

The limitations of research presented in this thesis are mainly due to the implementation of generalised input data, which were used due to the lack of an alternative. This was due to both the large size of the study area, Germany, and a lack of published data regarding (a) the occurrence of VAs in different fertilizer types (with temporal distribution) and (b) VA behavioural traits at each stage of the subsequent VA overland journey (solid-liquid partitioning and degradation in solid and liquid form).

Despite the highlighted limitations, the results of the compilation of presented studies highlight areas of high VA overland transport to surface water systems, such as along the border of North Rhine-Westphalia and Lower Saxony. It is recommended that a detailed, long term, physical study of VA overland transport is conducted across a relatively small area of agricultural land in this area and that VA overland transport in the same area is simulated using VANTOM; by comparing VANTOM results to real results, VANTOM can be validated and improved. The temporal variation of VAs in fertilizers, soils and surface water systems in the area, plus sorption coefficients and degradation constants, should be assessed via long-term sampling schemes. This would involve co-operation with farmers in the chosen area: all VA and fertilizer management criteria must be understood, including the masses of VAs that are administered (and pass through animals) at specific times of year, the masses of fertilizer that are applied to fields throughout each year, the influences of crop rotation on fertilizer management and the plough depth. Soil erosion and runoff rates could either be physically measured across the study area, or simulated using a process model which offers accurate results over small areas. If VANTOM is validated, then it could be used as a reliable tool for predicting rates of VA accumulation in soils and the overland transport therefrom, in study areas where the trends of VA occurrence in applied fertilizers are understood.

Further research should also be conducted into the fate of VAs that enter surface water systems. The downstream routing of VAs in water and sediment could be modelled and VA accumulation in areas of channel sedimentation could be identified. In particular, the effects of VAs on flora and fauna in affected areas should be explored, particularly in areas where human food sources (particularly freshwater fish or shellfish) or drinking water sources are potentially affected.

The results calculated by VANTOM (Study 4), plus the results of the water and sediment sampling schemes (Study 2) indicate that very low concentrations of VAs are transported to surface water systems (in the ng kg^{-1} to µg kg^{-1} range, which is not currently considered to be a threat to human health (Hamscher et al., 2005)). However, VANTOM results indicate that VAs are accumulating on agricultural fields in solid form. More detailed research should be conducted in order to assess if VAs are indeed accumulating rapidly over time, as this could lead to the increased contamination of plants that grow in those soils (Boxall et al., 2006), which are human food sources.

6 Acknowledgements

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Author's address

Miss Caroline Bailey, M.Eng.
Institute of Hydraulic Engineering and Water Resources Management
RWTH Aachen
Mies-van-der-Rohe-Str. 17
52056 Aachen