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Title

Assessment of Stormwater Pollutant Loads and Source Area Contributions with Storm Water Management Model (SWMM)

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Abstract

Decentralized urban runoff management requires detailed information about pollutant sources and pathways. However, scarce data of local water quality compel simplified approaches in water quality modelling. This study investigated the use of constant source concentrations in modelling pollutant loads. The source area contributions of total suspended solids, total phosphorus, total nitrogen, lead, copper and zinc were modelled with SWMM based on literature event mean concentrations (EMCs) for different land cover types and on-site rainfall and discharge data for a residential area in southern Finland. The simulated pollutant loads were compared with loads measured at the catchment outlet. Large differences were evident in the modelled catchment-scale and land cover specific loads, depending on the EMC data source. The simulated loads exceeded the measured loads especially during wet conditions, which was explained by the dilution effect of large stormwater volumes on measured EMCs. In addition, the mismatch was explained by the lack of local data for the source area EMCs and by the unaccountability of the mechanisms affecting loads along the pollutant pathways from source areas to sewer outlet. The spatial simulation of stormwater pollutant loads enabled the assessment of source area contributions at the catchment scale, as well as the pollutant pathways and the total diffuse pollution load. For a single pollutant, one or two important pollutant sources contributed the majority of the catchment load, which provides useful information for stormwater management. However, for a group of pollutants, no single land cover type dominated the pollutant loads, reflecting the challenges in decentralized water quality management in the scale of a residential area. Overall, the results emphasize that the widely used stormwater quality modelling with constant EMCs is uncertain even when on-site water quality and rainfall-runoff data from a catchment outlet are available.

Keywords

stormwater pollution, urban catchment, pollutant pathway, stormwater quality modelling, event mean concentration, land cover

1 Introduction

Stormwater pollutant load from urban areas is by nature diffuse pollution characterized by a variety of pollutants with different sources. To control runoff and its pollutants near their source areas, management concepts such as Low Impact Development (LID) has been developed. LID refers to decentralized systems of small-scale treatment units located at or near the source areas (Elliott and Trowsdale, 2007). The source areas include various urban land cover types, such as streets and roofs. In urban areas, impervious surfaces are considered the main contributors of runoff and pollutants (Lee and Heaney, 2003). On the other hand, pervious surfaces such as lawns may become important runoff and pollutant sources during large storms although many stormwater models ignore their contribution (Pitt et al., 2005).

For understanding stormwater quantity and quality, models are essential and need further development. Modelling is utilized for prediction, analysis and management of urban water quality and pollution, since monitoring of urban runoff quality requires extensive resources (Zhu et al., 2012). The need for improvement of modelling stormwater quality and LID systems is addressed by Elliott and Trowsdale (2007), who evaluated the performance and abilities of ten stormwater models. Elliott and Trowsdale (2007) identified improvement needs in model representations of runoff generation and pollutant processes, such as runoff from pervious surfaces and pollutant transport. Even currently available stormwater models are not fully exploited for water quality simulation (Petrucci et al., 2014). For example, the widely adopted US EPA SWMM, which is supplied with a water quality package (Rossman, 2015), is commonly used for runoff modelling, but less frequently extended to simulation of water quality (Niazi et al., 2017).

There are different approaches for simulating stormwater quality and estimating pollutant loads, and the chosen approach depends on the modelling target, as well as available data and resources. A typical process-based approach is to model stormwater quality with different buildup and washoff equations, which describe pollutant accumulation on the land surface during dry periods and wash off during rainy periods (Charbeneau and Barrett, 1998). In SWMM, the buildup is simulated with exponential function, power function or saturation equation, while the washoff is simulated with the exponential or rating curve equations (Rossman and Huber, 2016). With these buildup and washoff equations, the temporal variation of pollutant concentrations during an event can be simulated. A simpler modelling approach is to estimate washed off pollutant loads with flow-weighted event mean concentrations (EMC), assuming the pollutant concentrations in runoff are constant during an event (Charbeneau and Barrett, 1998). This EMC approach does not require modelling buildup (Rossman and Huber, 2016).

When simulating stormwater quality and estimating pollutant loads, practitioners prefer simple modelling approaches, e.g. average EMCs instead of process-based approaches with higher data requirements (Mourad et al., 2005; Rossman and Huber, 2016). The buildup and washoff equations include several parameters that are difficult to calibrate without on-site data. Representative parameter values for the buildup and washoff equations for different pollutants and geographic locations are rarely available in the literature, while average EMCs for different pollutants, source area types, and geographic locations are more accessible. To obtain feasible calibration and validation and to control the computational burden, simplified data-based model representations with EMCs have proven efficient (Gaume et al., 1998; Niazi et al., 2017). Using an average EMC when simulating multiple events can result in as accurate estimates of total pollutant load as when using process-based buildup and washoff approaches (Charbeneau and Barrett, 1998). For instance, Sage et al. (2015)

demonstrated that an EMC model produced comparable results with buildup and washoff models for total suspended solids (TSS) loads in street runoff.

Recent studies (Bonhomme and Petrucci, 2017; Sage et al., 2015; Wijesiri et al., 2016) criticize the application of buildup and washoff functions on a catchment scale, due to the spatial and temporal variations of the processes. In most applications, the same functions and parameters are used for the whole catchment without separating the different land cover types (Bonhomme and Petrucci, 2017). Due to the spatial variations of buildup characteristics, the use of one lumped parameter set leads to uncertainties and errors in the quality modelling (Liu et al., 2012). Increasing the spatial variability and dividing the catchment into several areas with separate parameter sets improves the model performance (Bonhomme and Petrucci, 2017). Similarly, when simulating long-term pollutant loads, the most accurate estimates are often generated using land use specific EMCs (Charbeneau and Barrett, 1998). A model with high spatial resolution and land cover specific average EMCs can be used to estimate the pollutant load contributions from different source areas in a catchment during multiple events. This information is needed by practitioners for outlining a cost-effective design and location prioritization of decentralized LID systems as a part of stormwater quality management.

Due to the practical limitations in the use of process-based water quality models in the absence of local monitoring data, there is a need to develop simple approaches in water quality modelling that take into account the spatial variability of urban areas. While SWMM is widely applied for runoff simulations, the model has rarely been applied to assess source area pollutant contributions with testing against on-site water quality data. Although buildup and washoff functions have been used in scientific literature, practitioners choose the simpler EMC washoff in water quality modelling and in the planning and design of stormwater management. This study aims to simulate urban pollutant loads with SWMM using a simple EMC washoff approach with a detailed spatial model. The purpose is to assess source area contributions within a typical spatial scale of a residential catchment (~11 ha), and to compare the simulation results against the measured loads at the catchment outlet.

The specific objectives include 1) evaluating the applicability of modelling stormwater pollutant loads from source areas with literature based average EMCs for different land cover types, and 2) assessing the importance of different urban source areas in catchment-scale diffuse pollution.

2 Materials and Methods

2.1 SWMM model of the Vallikallio catchment

The study catchment Vallikallio is an 11.4 ha residential area located in the city of Espoo, Finland (60°13'39"N, 24°49'3"E, Figure 1). The whole catchment has a separate pipe sewer network for stormwater runoff. A majority of the roofs and traffic related areas are directly connected to the sewer network. Records of precipitation, air temperature, discharge and water quality were available from the catchment outlet for five years (Sillanpää, 2013). Further details about the Vallikallio catchment are presented in Sillanpää and Koivusalo (2015).

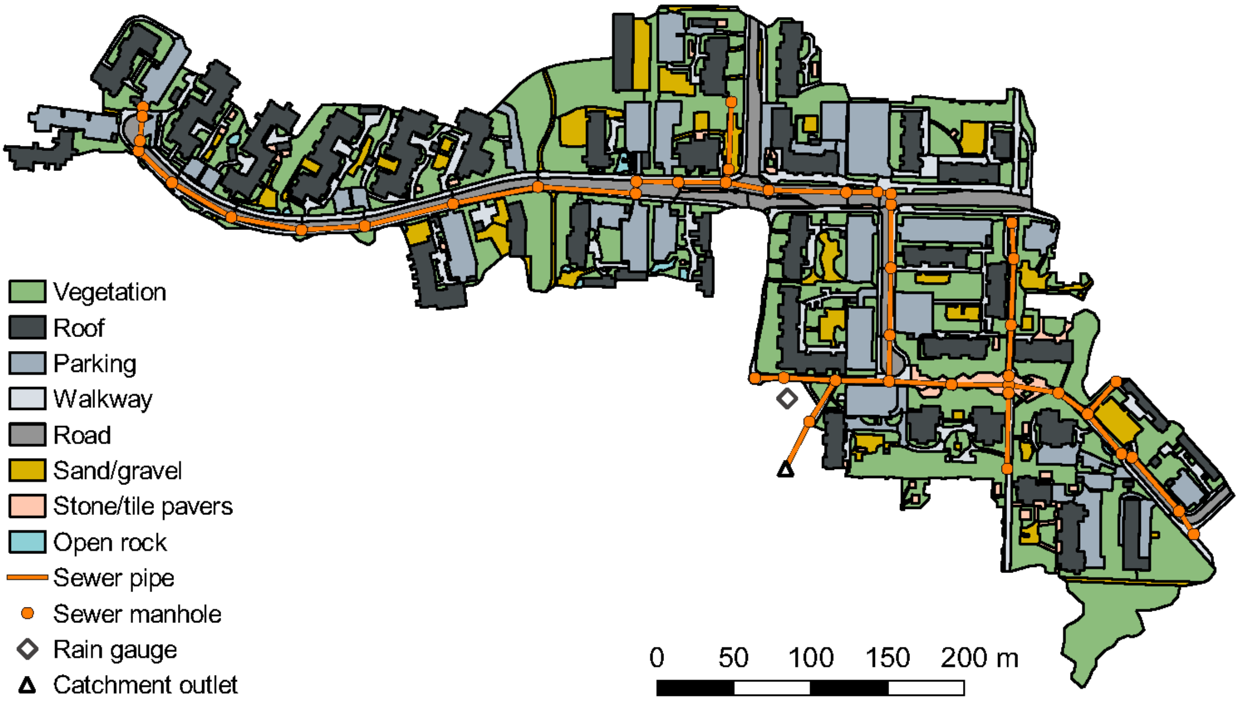

Figure 1. *SWMM model of Vallikallio, with source areas as subcatchments, the sewer network and catchment outlet.*

The catchment model in the present study was built on US EPA SWMM 5.0 (Rossman, 2015) and on hydrological model parameterization made by Raudaskoski (2016). The hydrological model had a detailed subcatchment discretization based on land cover types and contained over 600 subcatchments representing vegetation, roofs, asphalt, sand/gravel, stone/tile pavers or open rock (Figure 1). For the water quality and pollutant load simulations of the current study, the asphalted subcatchments were further categorized into parking areas, walkways and roads (Tuomela, 2017). The land cover types in the model had the following areal distribution: 38% vegetated areas, 19% roofs, 14% parking areas, 14% walkways, 6% roads, 6% sand/gravel, 2% stone/tile pavers, and 0.4% open rock. The impervious land cover types (roads, walkways, parking areas, roofs, and open rock) totaled 53% of the total catchment area.

Raudaskoski (2016) calibrated and validated the hydrological model against measured discharge from six storm events in Vallikallio. PEST (Doherty, 2018) was used to calibrate the values for Manning's roughness, depression storage and imperviousness for the different land cover types, as well as Manning's roughness of the pipes (Table 1). The calibrated hydrological model simulated storm events with Nash-Sutcliffe efficiency values ranging from 0.73 to 0.93.

Table 1. *Calibrated parameter values for the different land cover and surface types (Raudaskoski, 2016).*

Land cover or surface type	Manning's roughness (-)	Depression storage (mm)	Imperviousness (%)
Asphalted areas	0.016	0.826	94.1
Roof	0.0084	0.28	100*
Open Rock	0.05	3.16	100*
Stone/Tile Paving	0.019	0.3	84.9
Sand, Gravel	0.01	0.4	33
Vegetation, Lawns	0.5	2.45	0*
Pipes	0.015		

*not calibrated

In this study, SWMM 5.1 was used to simulate stormwater runoff and flow routing. The Green-Ampt method was used to simulate infiltration (Rossman, 2015). The soil in the catchment is mostly sandy till, and was given the infiltration parameters for sandy clay loam: suction head 219.64 mm, saturated hydraulic conductivity 1.524 mm/h and initial soil moisture deficit 0.154 (Guan et al., 2016). For flow routing in the sewer network, the dynamic wave routing scheme was used (Rossman, 2015). Evaporation rates were simulated in SWMM based on the measured daily maximum and minimum air temperature.

2.2 Water quality simulations

For water quality simulations in SWMM, the EMC washoff function was chosen. Consequently no buildup function was used as it is only required with the exponential washoff function (Rossman and Huber, 2016). This way the only parameter values required for the quality simulations were the land cover type specific EMC values. The studied stormwater pollutants were TSS, total phosphorus (TP), total nitrogen (TN), lead (Pb), copper (Cu) and zinc (Zn). As there were no local or national guidance values for EMCs, a literature review was made to identify possible values. Studies including EMC values for several different land cover types (Göbel et al., 2007; Heaney et al., 1999; Pitt and McLean, 1986) were preferred over studies of single land cover types, although they are scarce. Some studies included EMCs for only a limited number of source areas: e.g. Gilbert and Clausen (2006) studied runoff quantity and quality of asphalt, paver and stone driveways. To obtain the EMC values for all land cover types identified within the study catchment, values were combined from several literature references shown in Table 2. The literature-based average EMCs represented mean or median values from several events. For all six pollutants, the EMC values were grouped into three to five different sets with values assigned for each land cover type (Table 2) in order to simulate different alternatives. Uncertainties in catchment-scale and land cover specific loads were evaluated by comparing simulation outcomes resulting from various literature EMCs.

Table 2. *The literature-based EMC sets and values for each selected stormwater pollutant and land cover types in the Vallikallio model.*

Pollutants	**Land cover types**	**EMC set 1**	**EMC set 2**	**EMC set 3**	**EMC set 4**	**EMC set 5**
Total Suspended Solids (mg/l)	Parking area	1660 (e	440 (e	150 (d	173 (a	44 (g
	Walkway	20 (e	20 (e	7.4 (d	58 (a	46 (g
	Road	242 (e	232 (b	163 (d	662 (a	64 (g
	Roof	13 (e	41 (b	43 (d	27 (a	20 (g
	Open rock	11	11	11	11	11
	Stone/tile paving	20	20	15.8 (c	15.8 (c	15.8 (c
	Sand, Gravel	810 (e	810 (e	33.7 (c	33.7 (c	33.7 (c
	Vegetation, Lawns	11 (e	71 (b	12 (d	397 (a	75 (g
		EMC set 6	**EMC set 7**	**EMC set 8**	**EMC set 9**	**EMC set 10**
Total Phosphorus (mg/l)	Parking area	0.36 (e	0.244 (c	0.244 (c	0.62 (f	1.16 (a
	Walkway	0.8 (e	0.8 (e	0.8 (e	0.8 (f	0.8 (f
	Road	0.62 (e	0.31 (e	0.24 (b	0.49 (f	1.31 (a
	Roof	0.03 (e	0.1 (e	0.14 (b	0.04 (f	0.15 (a
	Open rock	0.05	0.05	0.07	0.2	0.2
	Stone/tile paving	0.36	0.162 (c	0.162 (c	0.62	1.16
	Sand, Gravel	0.2 (e	0.155 (c	0.155 (c	0.2	0.2
	Vegetation, Lawns	0.05 (e	0.05 (e	0.07 (b	0.2 (f	2.67 (a
		EMC set 11	**EMC set 12**	**EMC set 13**	**EMC set 14**	
Total Nitrogen (mg/l)	Parking area	3.1 (e	8 (c	2.2 (f	2.88 (d	
	Walkway	1.1 (e	1.1 (e	1.1 (f	2.34	
	Road	2.4 (e	2.2 (b	1.6 (f	5.9 (d	
	Roof	1.1 (e	0.71 (e	0.8 (f	6.17 (d	
	Open rock	1.1	1.1	1.1	2.34	
	Stone/tile paving	1.1	0.7 (c	1.1	2.34	
	Sand, Gravel	1.3 (e	1.6 (c	1.3 (f	2.34	
	Vegetation, Lawns	0.94 (e	0.95 (b	1.3 (f	2.34 (d	
		EMC set 15	**EMC set 16**	**EMC set 17**		
Lead (µg/l)	Parking area	250 (e	137 (d	22 (a		
	Walkway	80 (e	107 (d	17 (a		
	Road	180 (e	170 (d	55 (a		
	Roof	30 (e	69 (d	21 (a		
	Open rock	30	107	17		

	Stone/tile paving	80	107 (d	17
	Sand, Gravel	30 (e	107	17
	Vegetation, Lawns	0 (e	9 (d	17
		EMC set 18	**EMC set 19**	**EMC set 20**
Copper (µg/l)	Parking area	100 (e	80 (d	15 (a
	Walkway	20 (e	23 (d	15
	Road	40 (e	97 (d	56 (a
	Roof	100 (e	153 (d	15 (a
	Open rock	20	23	15
	Stone/tile paving	20	23	15
	Sand, Gravel	20 (e	23 (d	15
	Vegetation, Lawns	0 (e	11 (d	13 (a
		EMC set 21	**EMC set 22**	**EMC set 23**
Zinc (µg/l)	Parking area	520 (e	400 (d	450 (f
	Walkway	60 (e	585 (d	60 (f
	Road	180 (e	407 (d	160 (f
	Roof	320 (e	370 (d	310 (f
	Open rock	40	585	40
	Stone/tile paving	60	585	40
	Sand, Gravel	40 (e	585 (d	40 (f
	Vegetation, Lawns	0 (e	80 (d	40 (f

References: a) Bannerman et al. (1993), b) Duncan (1999), c) Gilbert and Clausen (2006), d) Göbel et al. (2007), e) Heaney et al. (1999), f) Pitt and McLean (1986), g) Waschbusch et al. (1999)

The EMC values for pavers were rare in the literature, except for the values found for driveways in Gilbert and Clausen (2006). Since many of the paved areas in the catchment were located on driveways or walkways, the paved areas were given the same EMC values as the walkways (Table 2). The EMC values for open rock were not found from the literature, and thus open rock was assigned the same value as vegetated areas or walkways. However, the areal coverage of open rock was minor (0.4%) in the catchment and thus not considered to be an important source of pollutants.

The runoff and pollutant contributions of the subcatchments were modelled for each pollutant and EMC set (Table 2). Rainfall data with multiple events from two summer periods (June-August) in 2005 and 2006 were used. These two summers were chosen due to their contrasting weather conditions: the summer 2005 was wet with 348 mm of precipitation while the summer 2006 was dry with 52 mm of precipitation.

In SWMM, the subcatchments can be connected to a downstream subcatchment, a sewer network, or a channel, creating flow paths within the catchment. The subcatchments receive runoff and pollutants from rainfall and upstream connected subcatchments. The subcatchments generate runoff and pollutant loads to the downstream subcatchments after accounting for losses such as depression storage, infiltration, and evaporation. The subcatchment connections in the model define how runoff is routed between the subcatchments and further to the sewer network.

For each simulation, SWMM automatically produces subcatchment summaries including contributions from upstream areas. Hence, the pollutant washoff per land cover type had to be calculated outside the SWMM interface by removing the influence of upstream catchments. First, to determine the pollutant washoff from each subcatchment, the runoff inputs from the upstream connected subcatchments were removed and the load was calculated based on the remaining runoff volume. Second, total source area loads and runoff volumes were calculated by grouping the subcatchments based on land cover type. Third, total catchment load and total catchment runoff volume were calculated by summing up the source area loads and volumes. Fourth, an average volume-weighted mean concentration was calculated for the total catchment area for each simulation period, by dividing the total catchment load with the simulated total runoff volume. Later in the results, this is referred to as a Site Mean Concentration (SMC).

The simulation results were compared against the measured values for the two summers separately. Sillanpää (2013) monitored the water quality in the Vallikallio catchment with automatic flow-weighted sampling, and determined long-term pollutant loads, SMCs and EMCs. Measured TSS, TP and TN loads for the current study were derived from 29 event-scale EMCs from the Vallikallio catchment outlet (Sillanpää and Koivusalo, 2015). On-site water quality data from different land cover types were not available. Since no metals were measured in Vallikallio, the simulated metal loads (Pb, Cu and Zn) were compared against loads estimated from off-site average EMCs from a similar residential catchment in Lahti, Finland (Valtanen et al., 2014). The monitored pollutant EMCs were multiplied with the simulated runoff from Vallikallio to estimate reference loads comparable with the simulated loads.

The performances of the literature-based EMC sets (Table 2) were evaluated by first comparing the simulated SMCs with the monitored SMCs from Vallikallio, and in case of metals, from Lahti. Second, the simulated loads were compared against the monitored loads. A subjective criterion of ±50% for the simulated SMCs was set as an acceptable deviation from the monitored value. Based on these criteria, one set of EMC values was chosen for each pollutant to further assess the importance of different pollutant sources in the catchment-scale pollution.

3 Results and Discussion

3.1 Pollutant loads with different EMCs

The simulations with different EMC sets (Table 2) produced largely variable loads in catchment-scale (Figure 2a-f). During the wet summer of 2005 about 19000 m^3 of runoff and large pollutant loads were estimated, whereas the dry summer of 2006 yielded about 1900 m^3 of runoff and clearly lower pollutant loads. The evaporation loss was around 5000 m^3 and the infiltration loss around 15000 m^3 during the wet summer, while being around 1300 m^3 and 2700 m^3 during the dry summer. Due to the use of constant source area EMCs, the differences in the modelled loads between the two summers were directly proportional to the differences in runoff. However, the differences in the measured catchment loads between the two summers were much smaller than the simulated differences. Overall, the simulated loads were closer to the measured loads during the dry summer whereas the simulations overestimated loads in wet conditions (Figure 2a-f). Based on the measurements, the wet summer produced two to nine times larger pollutant loads than the dry summer. Based on the simulated loads, however, the wet summer produced nine to 21 times larger loads than the dry summer. In this case, the selected constant concentrations reflected the dry summer conditions better than the wet summer. Sillanpää and Koivusalo (2015) observed based on a 5-year data set containing in total of 150 rainfall events that at the Vallikallio catchment the large rainfall events dilute the pollutant concentrations, but produce larger loads than the smaller events. The simulations overestimated the pollutant loads during wet conditions, because simulating each rainfall event with the same constant concentration did not reflect the dilution of pollutant concentrations that occurs during larger rainfall events.

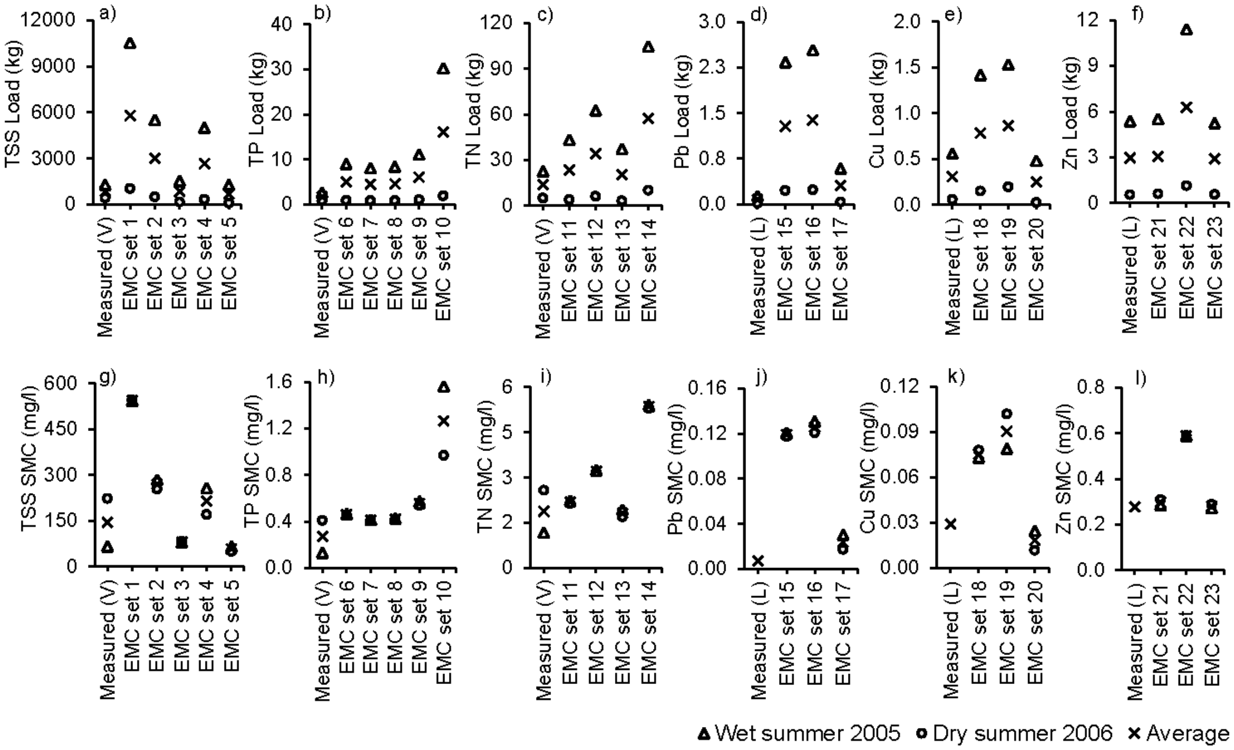

Figure 2. *TSS (a, g), TP (b, h), TN (c, i), Pb (d, j), Cu (e, k) and Zn (f, l) pollutant loads and SMCs for the wet summer 2005 and dry summer 2006, simulated with different EMC sets (Table 2) and compared with measured values from Vallikallio (V) and Lahti (L).*

In addition to assuming constant EMCs for all weather conditions, the SWMM application did not account for processes affecting pollutant transport in the sewer system. These processes might reduce or increase pollutant loads as water travels through the conveyance system to the outlet (e.g. Borris et al., 2017; Ma et al., 2018; Wright et al., 2011). To reduce the error between the measured and simulated outfall loads, a pollutant transport function would be needed in the modelling process (Bannerman et al., 1993). Currently, it is possible to model pollutant treatment and decay in SWMM by assigning removal rates to the nodes in the model (Niazi et al., 2017); however, this feature was not utilized in the simulations of this study.

Based on the measured site mean concentrations from Vallikallio (Figure 2g-i), the SMC of the dry summer was at least double when compared to the wet summer. Due to the use of constant EMCs in the simulations, the SMCs determined with simulated loads and runoff did not reflect this dilution and were of the same order of magnitude for both summers (Figure 2g-i). Only a few exceptions occurred where the simulated SMCs differed between the wet and dry summers, and these exceptions were associated with the EMC sets including distinct differences in the literature-based EMC values between the vegetated and impervious land cover types. For example, when using TSS EMC set 4 (Figure 2g) and TP EMC set 10 (Figure 2h), the wet summer produced higher pollutant concentrations than the dry summer. This difference is due to the very high EMC values (Table 2) for vegetated source areas that started generating runoff during the wet conditions and increased the pollutant load. On the contrary, when simulating Cu EMC set 19 (Figure 2k), the dry summer produced a higher SMC than the wet summer. This difference is due to the dilution caused by the larger simulated runoff contribution from vegetated areas with much lower EMCs for copper compared with the impervious land cover types (Table 2).

Overall, the differences in both the simulated SMCs and pollutant loads during the dry and wet summers (Figure 2) are explained by the different amounts of runoff produced from different land cover types. In addition, the differences are explained by the changing land cover type specific EMCs in different EMC sets (Table 2). The total pollutant load was increased by land cover types assigned with high EMCs and with a large runoff generation potential. For example, the simulation of TSS load with EMC set 1 (Figure 2a), the TP load with EMC set 10 (Figure 2b) and the TN load with EMC set 14 (Figure 2c) generated pollutant loads clearly larger than the measured loads, as well as the loads simulated with different EMC sets for the same pollutant. These three EMC sets included higher EMC values for several land cover types when compared with other literature-based values for the same pollutant. The results indicate that using land cover specific and literature-based average EMCs can result in reasonable estimates of long-term pollutant loads only when the representativeness of the EMC data can be ensured for the local conditions. It is clear that the EMC approach becomes increasingly uncertain for analyzing pollutant loads or concentrations short-term or under varying weather conditions. However, as described above, the EMC approach reveals mechanisms about the importance of different source areas under changing weather conditions despite the high uncertainties in absolute loading rates.

3.2 Importance of pollutant source areas in catchment-scale loads

As with the catchment-scale loads, the water quality simulations with different EMC sets (Table 2) yielded large variations in pollutant loads estimated for different land cover types (Figure 3). This again illustrates the high uncertainties in the load estimates produced based on literature references. 10-40-fold differences between the minimum and maximum loads for certain land cover types were observed for all studied pollutants except for TN, for which the variations in the EMC values between the land cover types were somewhat modest compared with other studied pollutants. However, even for TN, a 10-fold difference between the minimum and maximum load for roofs was observed, which seem to be the most significant source area for TN washoff. Particularly large variations in land cover specific loads in Figure 3 were observed for parking areas (TSS, Pb, Cu), walkways (Pb, Zn), roofs (Cu), vegetation (TSS, TP), sand surfaces (TSS, Zn), and pavers (Pb, Zn).

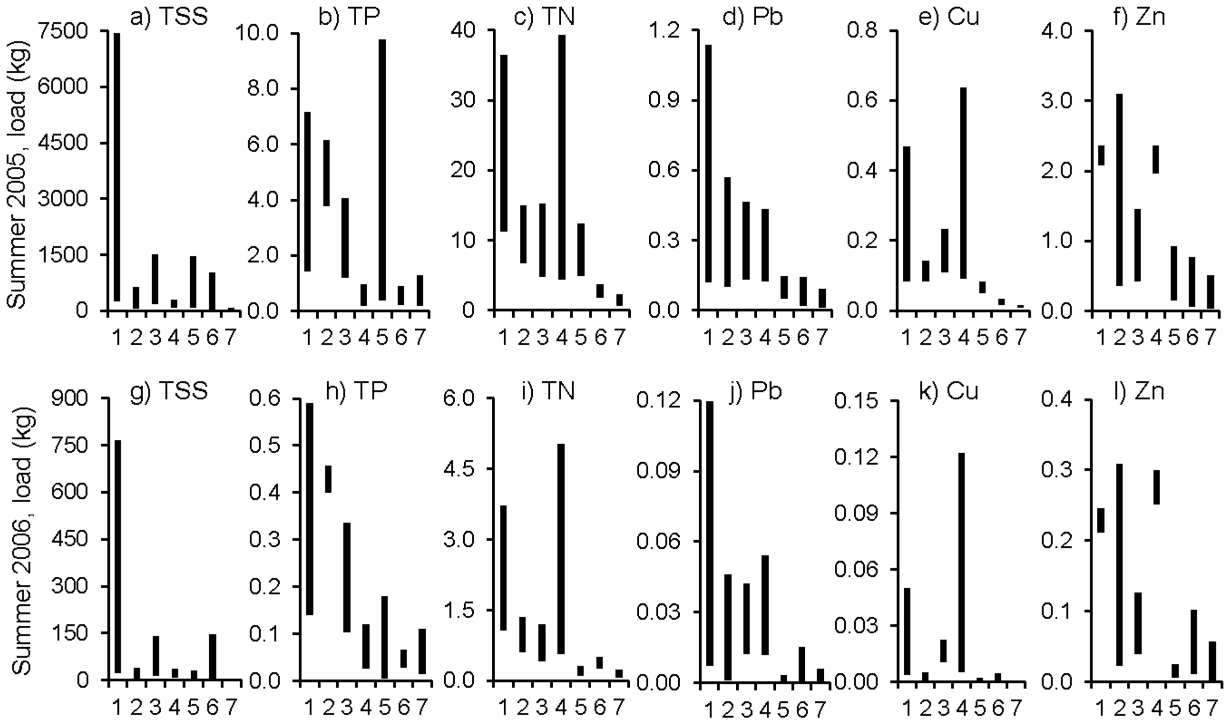

Figure 3. *Load ranges for different land cover types for the wet summer 2005 and dry summer 2006 simulated with all EMC values presented in Table 2. Numbers 1-7 refer to different land cover types as follows: 1 Parking, 2 Walkways, 3 Roads, 4 Roofs, 5 Vegetation, 6 Sand and 7 Pavers. The land cover type rock was excluded, due to the very small pollutant contributions.*

Based on the best correspondence between the measured and modelled catchment loads in Figure 2, one EMC set was selected for each pollutant to further refine and evaluate the source area contributions of runoff and pollutant loads within the study catchment (Figure 4). The selected EMC sets were the following: TSS set 3, TP set 6, TN set 13, Pb set 17, Cu set 20 and Zn set 23 (Table 2).

Different land cover types in the Vallikallio catchment contributed to the simulated runoff and pollutant loads unevenly (Figure 4) revealing the main source areas behind different pollutants. Constructed impervious areas, such as roads, roofs, parking areas and walkways, are often emphasized as the key source areas for urban diffuse pollution for most pollutants (Bannerman et al., 1993; Waschbusch et al., 1999). In Vallikallio, impervious source areas contributed the highest volumes of runoff (76-86%) and the pollutant contribution was over 75% for all pollutants. During the dry summer 2006, nearly all pollution (94% on average) originated from impervious surfaces.

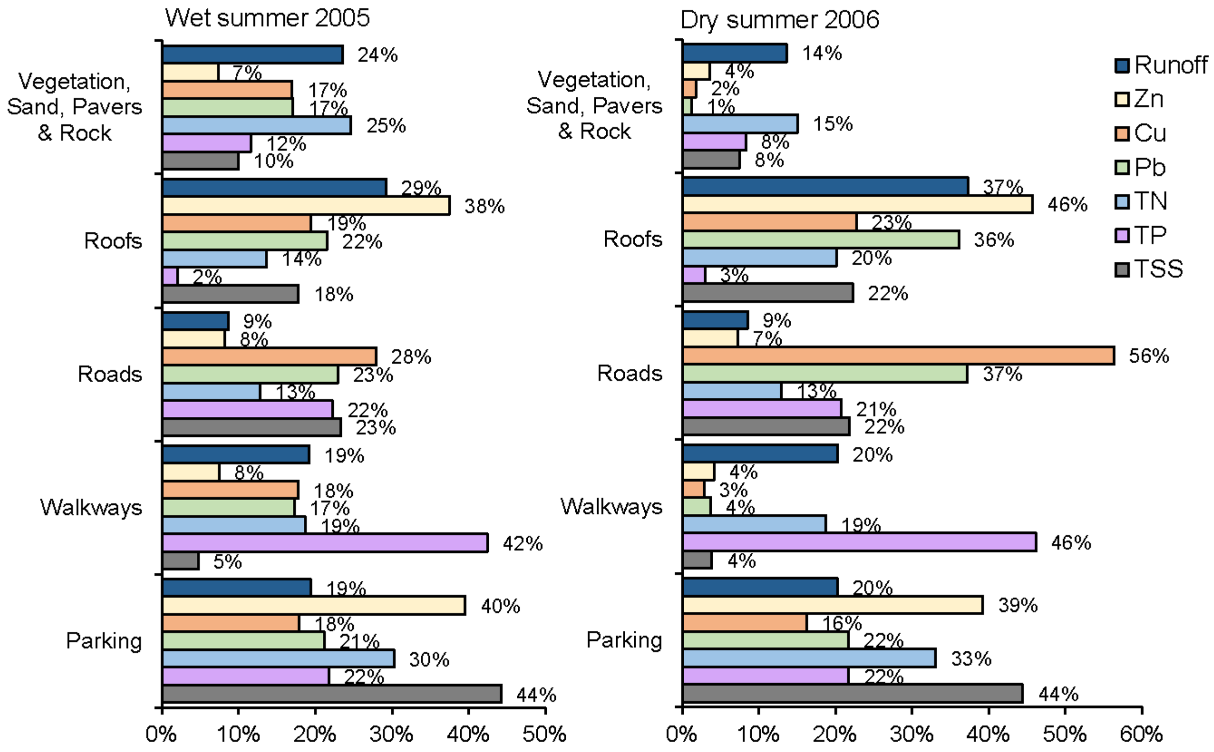

Figure 4. *Source area contributions of the runoff and pollutant loads, simulated with selected EMC sets for the wet summer 2005 and dry summer 2006.*

The runoff and pollutant contribution from source areas are affected by several factors from weather conditions to areal characteristics (Heaney et al., 1999). The impact of the weather conditions was most evident in the runoff generation and pollutant contributions from the vegetated areas. The vegetated areas generated 3% and 15% of the total runoff during the dry summer 2006 and the wet summer 2005, respectively. In addition, the load contributions from pervious land cover types clearly increased in wet conditions compared with the dry summer, particularly in the case of Cu, Pb, and TN (Figure 4). The results support the conclusions of Pitt et al. (2005), who observed that pervious surfaces become important contributors during larger storms. In relation to the pollutant contributions from impervious source areas, the pollutant washoff from vegetated areas was still small.

In addition to the weather conditions, the source area characteristics affect the runoff and pollutant contribution within a catchment. According to Fraga et al. (2016) the main source area characteristics are the relative contributing area, as well as the physical surface type and material. In the Vallikallio catchment, the vegetated areas (38%) had the largest areal coverage, followed by roofs (19%), parking areas (14%) and walkways (14%). Vehicular roads covered only 6% of the residential catchment, hence reducing their contribution to the catchment-scale loads. Land cover types with a small area (≤ 6%), such as open rock and paved areas had a minor influence on the total runoff and pollutant loads. The roofs had the second largest areal coverage and contributed the largest proportional loads of metals, especially Zn, which is in line with Bannerman et al. (1993) and Petrucci et al. (2014). The reason behind the high reported concentrations of Zn, Cu, and Pb in roof runoff are the roof materials (Bannerman et al., 1993; Borris et al., 2017). Thus, the heavy metal contribution of roofs varies depending on the roof materials in the local catchment, and are difficult to determine based on only literature values.

Previous studies have emphasized different pollutant sources in terms of their importance in urban runoff pollution. According to Bannerman et al. (1993), roads are critical source areas for most pollutants and contribute the largest share to the pollutant loads. In line with this, Waschbusch et al. (1999) and Pitt et al. (2005) reported that roads are the largest contributors of solids, especially during small low-intensity rains. Fraga et al. (2016) pointed out roads, parking areas and roofs as major sources of TSS, Pb, Cu and Zn. It is noteworthy that in Vallikallio, no single land cover type seemed to dominate the catchment loads for all studied pollutants (Figure 4). The parking areas in Vallikallio were usually a larger pollution source than roads, especially in the case of TSS and Zn. The differences in pollutant loads between parking areas and roads were both due to the chosen EMC values (Table 2) and due to the twofold size of parking areas compared with the area of roads. Despite the smaller area, the roads proved to be significant contributors of Pb and Cu, which relates to the high concentrations used in the simulations. Walkways contributed to nutrient loads, especially TP. The uneven pollutant contributions from different land cover types highlight the importance of understanding the catchment-specific runoff generation and pollutant loads and pathways when developing efficient stormwater management strategies. Although simple rules in guidelines and regulations are favored, focusing on a single source area type in runoff quality management, e.g. on roads, parking areas, or roofs, leads to ineffective water quality control.

3.3 Advantages and disadvantages of the EMC modelling approach

The water quantity and quality models are complex with connected subcatchments, sewer networks, pollutants and LID controls. The processes in the model should according to Niazi et al. (2017) be represented in a simplified way to gain high computational speed in model execution. Modelling stormwater quality with EMCs is a widely adopted but seldom studied approach, which exploits concentration values obtainable from literature, and does not require extensive monitoring and parameter calibration. However, using constant source area EMCs is a simplified representation of reality and the uncertainty of the results increases when the study periods and events become shorter.

When simulating pollutant contributions with SWMM, a detailed subcatchment discretization is an advantage. In stormwater modelling, a catchment is typically classified based on land use categories, which commonly are residential, commercial or industrial (e.g. Butcher, 2003; Charbeneau and Barrett, 1998). A coarse discretization based on the land use category keeps the model parameterization parsimonious, while it describes some spatial variability of the catchment characteristics. This type of coarser and simplified discretization is a limitation if a catchment has heterogeneous surfaces and results are needed in a small scale (Niazi et al., 2017). In the current study, it was important to discretize the heterogeneous catchment based on detailed land cover, to take into account the water quality differences between different source areas. Not because of runoff generation but because of water quality, asphalted areas had to be further divided into roads, parking areas and walkways. Previous studies have suggested that a detailed subcatchment discretization improves the accuracy of runoff simulations in ungauged catchments (Krebs et al., 2014, 2016) and increases the performance (Petrucci and Bonhomme, 2014). We assume that the same applies to water quality modelling at least by a better incorporation of pollutant pathways within the catchment and by a use of fixed parameterization of similar land cover types. In this study, the use of a detailed model and land cover specific EMCs was an approach that enabled to simulate and assess the variation of pollutant contributions from different source areas.

A detailed model discretization based on land cover types increases the amount of subcatchments and requires higher effort than a more conventional and coarser model discretization with larger areas and mixed land cover types. The linked subcatchments formed complex flow paths between each other (Figure 5). As an example, runoff can be generated in a lawn, flow over a paved walkway and then move to a parking area before entering the sewer network. A clear advantage of the adopted approach is that runoff and pollutants can be more accurately routed through the catchment, e.g. around buildings and through different types of source areas, and the contributing areas of the sewer manholes become accurate. For instance, Krebs et al. (2014) observed that a high-resolution model parameterization increased the accuracy of flow peaks and enabled determination of surface specific parameters, to support e.g. LID simulations.

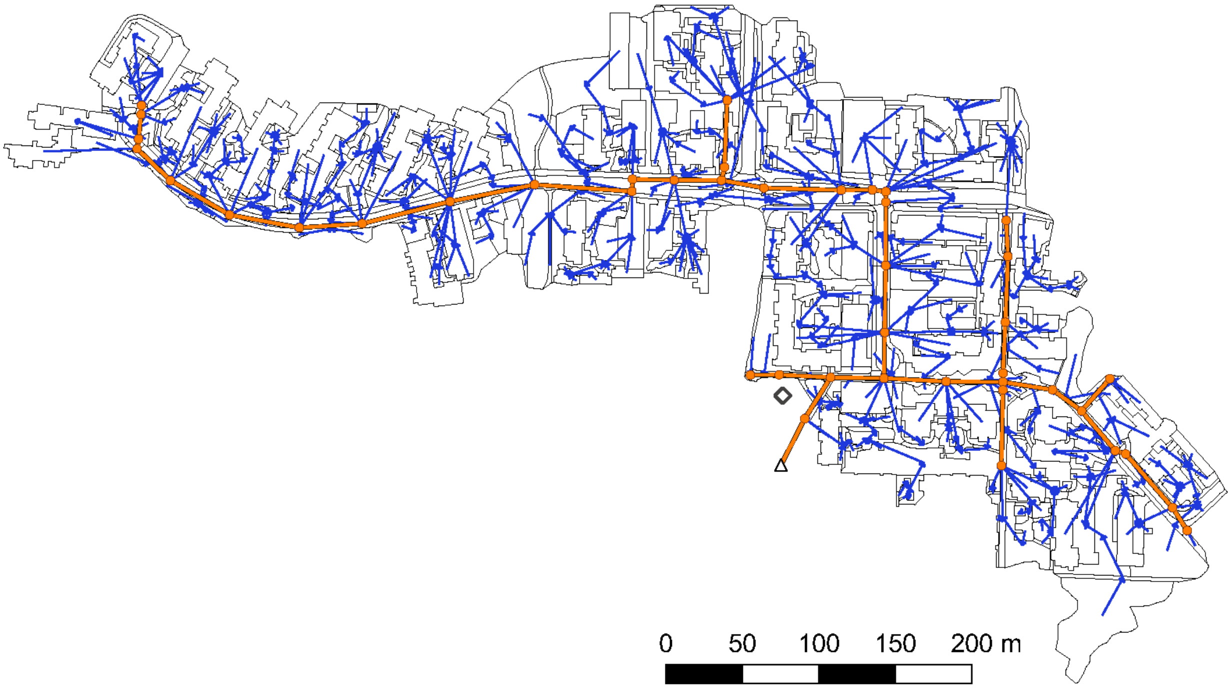

Figure 5. *The SWMM flow paths between subcatchments and the sewer network (illustration created with the InpToGIS-tool by Tero Niemi/Aalto University).*

Modelling pollutant loads with literature EMC values involves uncertainties but generates valuable information. The results from stormwater quality modelling can be assumed hypothetical without local measurements available for validation and calibration (Rossman and Huber, 2016). According to Fraga et al. (2016), stormwater models may perform well when stormwater is quantified and routed, but the stormwater quality predictions are rough and limited. For accurate information about source area contributions of stormwater pollutants, the source areas within a catchment should be monitored. In regular design situations, local measurements and detailed data from land cover types within the catchment are rarely available and one should be careful in selecting reference values from literature. The EMC sets used in this study can be utilized in pollutant load modelling in similar catchments, as long as the uncertainties are recognized.

The current study demonstrates the application of the detailed spatial model and land cover specific EMCs in an urban residential area, but leaves behind research questions: it is not assessed how the current model compares with other types of urban water quality models and how the large uncertainties arising from varying EMCs should be encompassed into the results and further to practical stormwater planning. In addition, the processes occurring on the pathway from the source area to the sewer network and inside the sewer pipes deserve more attention.

4 Conclusions

The stormwater pollutant load modelling with literature based EMCs yielded highly variable loads, both on catchment-scale and per land cover type. In comparison to the monitored loads, the simulated loads were often overestimated. This overestimation was explained by the literature EMC values that did not correspond to the local conditions and the EMCs that did not reflect the dilution impacts of changing stormwater volumes on pollutant concentrations. Modelling pollutant loads with EMCs involve large uncertainties, especially if local data for calibration and validation are lacking. However, modelling with EMCs is the most common approach used by practitioners and considered feasible if no other data are available.

The assessment of source area contributions showed that no single land cover type dominate the pollutant load contribution on a catchment scale, which highlights urban runoff as a diffuse pollution source. In general, constructed and impervious source areas contributed the largest runoff and pollutant loads, even though an increased contribution from pervious source areas was noted during wet conditions. The source area contributions depended on the weather conditions, the runoff quantity, the areal coverage of the land cover type in the catchment, and the magnitudes of the literature based EMC values. Based on the results, management strategies emphasizing treatment of runoff from single sources, such as road or roof runoff, may lead to inefficient pollution mitigation due to pollutant- and weather-dependent variations in source area contributions. Modelling pollutant loads with detailed model discretization based on land cover provide better understanding of the importance of different pollutant sources.

In addition to lacking monitoring data for calibration and validation, current challenges in stormwater quality modelling were related to the transport of pollutants along the flow paths within the catchment and inside the sewer networks. Evaluating the reliability of simulated source area loads based on comparison against measured outlet loads is challenging when the processes occurring during the pollutant transport are not considered.

Despite uncertainties, stormwater pollution modelling and information about local source area contributions is important for prioritizing stormwater management options and designing effective decentralized LID units for pollution reduction. In the future, more research is needed to characterize representative concentrations in local climate conditions and to further understand the processes affecting the transport of pollutants over a series of connected land cover types.

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