PROPER PROJECT
WP1 - PREDICTION OF POLLUTANT LOADS AND CONCENTRATIONS IN ROAD RUNOFF
Task 1.4. Assessment of tools to predict road runoff water quality

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DELIVERABLE 1.4

Title

PROPER PROJECT - WP1.PREDICTION OF POLLUTANT LOADS AND CONCENTRATIONS IN ROAD RUNOFF
Task 1.4. Assessment of tools to predict road runoff water quality

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PROPER PROJECT - WP1.PREDICTION OF POLLUTANT LOADS AND CONCENTRATIONS IN ROAD RUNOFF

Task 1.4. Assessment of tools to predict road runoff water quality

Abstract

This report stands for the PROPER project deliverable 1.4 and concerns the results from task 1.4: *Assessment of tools to predict road runoff water quality*.

Following the literature review and the evaluation of the models conducted in previous tasks from WP1, the aim of the present task is to test the tools and methods selected in deliverable 1.2 (D1.2) for the case studies presented in deliverable 1.3 (D1.3).

In order to accomplish the task objectives, this report starts with the presentation of the four tools selected in D1.2 to predict road runoff water quality, namely, PREQUALE, HAWRAT, Multiple Linear Regression by Kayhanian et al. (2007) and SELDM.

The monitoring data from different roads and countries in Europe are presented. The data set comprises 22 case studies/roads covering wide range and diverse characteristics from 7 different countries namely Norway, England, Switzerland, France, Ireland, the Netherlands and Portugal. The roads and the monitored pollutants are briefly characterized in the present report.

All the tools were tested for each case study and the results of each tool were compared to the monitoring data. The overall results show that the tools are not able to predict the road runoff pollutant concentrations. It is understood that the work done within these tasks from the PROPER project is very valuable in terms of conclusions and guidelines for the future practice and approaches to prediction of road runoff pollutant concentrations. It is not recommended to support decisions based on using road runoff prediction tools that were not established for the site/region/country or that are outdated.

Keywords: Road runoff, pollution, predicting tools, monitoring data

Table of contents

List of Figures

List of tables

1 | Introduction

The project PROPER is funded by the Conference of European Directors of Roads (CEDR) and regards the characterisation and prediction of road runoff pollution, the evaluation of its potential impacts on receiving water bodies and related ecosystems and the evaluation of treatment systems for impact mitigation during operation and construction of roads. The project has started in September 2017 and it will last until October 2019[1].

The work programme is organised in 6 Work Packages (WPs) where WPs 1 to 4 correspond closely to the scientific objectives of the project, namely:

– **WP1:** Prediction of pollutant loads and concentrations in road runoff;
– **WP2:** Assessing the vulnerability of European surface and ground water bodies to road runoff during the building and operating of roads;
– **WP3:** Sustainable assessment of measures and treatment systems for road runoffs;
– **WP4:** Sustainable assessment of measures and treatment systems for road runoffs during construction work.

WP5 focuses on ensuring that maximum impact is achieved through the implementation of a robust dissemination strategy with **WP6** outlining the project management activities which underpin successful project completion.

This report concerns WP 1 and it is the last one communicating the WP outputs and task results. The previous steps of the work (reported in deliverables D1.1; D1.2; D1.3 and D1.5) have been:

- Preselection of predicting models made in task 1.1, based on literature review and inputs from the consortium partners and the project International Advisory Board (IAB) members;
- Task 1.2 provided an assessment of these preselected models taking into account their requirements, the easiness of applicability and the consistency of the output results. The assessment was mainly performed by analysing the manuals, papers and reports that were produced to help the implementation of each tool (at that stage the models were not implemented). The 4 selected tools were: PREQUALE; HAWRAT; Kayhanian et al. (2007) and SELDM;
- In Task 1.3 monitoring data were collected from selected representative sites, within Europe, for the assessment of the prediction tools mentioned above. D1.3 presented and explained the data for the 22 case studies.

[1] The initial Project deadline would be the end of August 2019. CEDR has agreed with the project consortium to extend the project duration until October, allowing the accomplishment of a final joint meeting of the 3 projects within the 2016 Call, to be held in Lisbon, Portugal.

- In task 1.5 emission models and atmospheric concentration models were discussed, including issues that will affect the concentrations in road runoff, such as emissions and pathways from the roads (via runoff or via atmospheric processes).

This report D1.4 within task 1.4 compares the real Site Mean Concentrations (SMC) in road runoff of each road with the results from using each of the 4 tools. The main output from this task is the evaluation of the overall accuracy of each tool and therefore their potential for general use at an European level.

2 | Tools to predict road runoff water quality

2.1 Overview

Taking into consideration the literature review presented in the PROPER report D1.1 a total of 6 tools to predict road runoff water quality were selected. These tools were presented and analysed in the PROPER report D1.2, where a detailed description of each tool, including its background and theoretical framework is provided.

The assessment was focused on 3 parameters, namely: i) data requirements, ii) applicability and iii) output results.

A score from 1 to 3 was given to each parameter. At the end, the sum of the scores allowed the selection of these 4 tools:

– Prediction of road runoff Quality (PREQUALE) (Barbosa *et al*., 2011)
– Highways Agency Water Risk Assessment Tool (HAWRAT) (Crabtree *et al*., 2008)
– Multiple linear regression (Kayhanian *et al*., 2007)
– Stochastic Empirical Loading and Dilution Model (SELDM) (Granato, 2013)

The models calculate either the concentration of each event (Event Mean Concentration, EMC) in road runoff or the Site Mean Concentration (SMC) for the site. If a model calculates EMC only, then SMC is calculated by averaging several EMCs.

The main characteristics of these four tools under evaluation are summarised in the following subsections.

2.2 Prediction of road runoff Quality (PREQUALE, Portugal, 2011)

In the scope of the research project G-Terra funded by the Portuguese Foundation for Science and Technology and coordinated by the National Laboratory for Civil Engineering (LNEC), several roads were monitored in terms of the pollution of road runoff between 2002 and 2006 (Barbosa *et al*. 2011). Using the monitoring data and the previous studies on road runoff monitoring in Portugal, a new tool called PREQUALE was developed.

The model PREQUALE is based on the characteristics and monitored data for six Portuguese roads located in different climatic regions within Portugal. In order to catch the variability of the annual mean precipitation in Portugal, the choice of the monitoring sites covered values ranging from 560 mm to 1200 mm. Similarly, different relevant highways have been selected to the study. The average annual daily traffic (AADT) of the selected sites ranged from around 6500 up to 30300 vehicles per day. The AADT values are related to the country's population and the rate of use of highways. The monitored data was generated with automatic and continuous sampling of road runoff along precipitation events, combined with flow and rainfall measurements. For each road, the Site Mean Concentration (SMC) is based on an average of 8-10 independent runoff events.

The tool is based on a multiparametric equation with the following input variables:

Drainage Area (*DA* in km^2): area which contributes with runoff to the discharge point during a rainfall event;
Impervious fraction (*IF* in %): the percentage of the total drainage area which is impervious;
Average annual rainfall volume per event (defined by a duration equal to the concentration time of the basin) (*AR* in mm);
Annual average precipitation (P_{annual} in mm).

This tool aims at directly predicting SMCs. The multiparametric equation is the following:

$$SMC_p = a_i \left(DA^{\beta_1} \times IF^{\beta_2} \times AR^{\beta_3} \times P_{annual}{}^{\beta_4} \right)$$

where SMC_p is the estimated Site Mean Concentration of each pollutant (mg/l) and a_i, β_1, β_2, β_3 and β_4 are the regression coefficients.

The current version of PREQUALE allows the prediction of SMCs for TSS, COD, Fe, Zn and Cu. Note that the selection of these key parameters was done by Barbosa et al. (2011) based on comparison of concentrations found in road runoff with a Portuguese decree-law (Decreto-Lei 236/98) regarding wastewater point discharges. It was used as benchmark, since there is no specific regulation for road runoff. All the 5 parameters showed concentrations similar our above the limits for discharge allowed in the decree-law.

The regression coefficients to be used in PREQUALE are presented in Table 2.1, meaning it is a tool simple to be used.

Table 2.1. PREQUALE regression and correlation coefficients.

Parameter	a_i	β_1 (DA)	β_2 (IF)	β_3 (AR)	β_4 (P_{annual})
TSS	1.22×10^{44}	0.257	-5.085	-28.797	-2.945
COD	1.91×10^{25}	0.1644	-3.165	-16.914	-1.064
Fe	9.20×10^{44}	-0.1491	-6.546	-28.229	-3.371
Zn	1.15×10^{5}	-0.135	-1.08	-0.323	-1.296
Cu	3.08×10^{1}	0.036	-0.705	0.396	-0.702

2.3 Highways Agency Water Risk Assessment Tool (HAWRAT, UK, 2008)

The Highways Agency Water Risk Assessment Tool[2] (HAWRAT) was developed by the Highways Agency from the United Kingdom as a standalone application aiming at assisting highway designers and operators in the decision if whether or not pollution mitigation measures are needed.

Besides the prediction of runoff quality, HAWRAT comprises equations for predicting the impact of the runoff on receiving rivers and streams. HAWRAT has therefore three steps as shown in Figure 2.1: *Step 1* concerns road runoff pollution prediction; *Step 2* is related to the impacts on the receiving water bodies and *Step 3* deals with mitigation measures. For the objective of the current task, only step 1 is used and was taken into consideration.

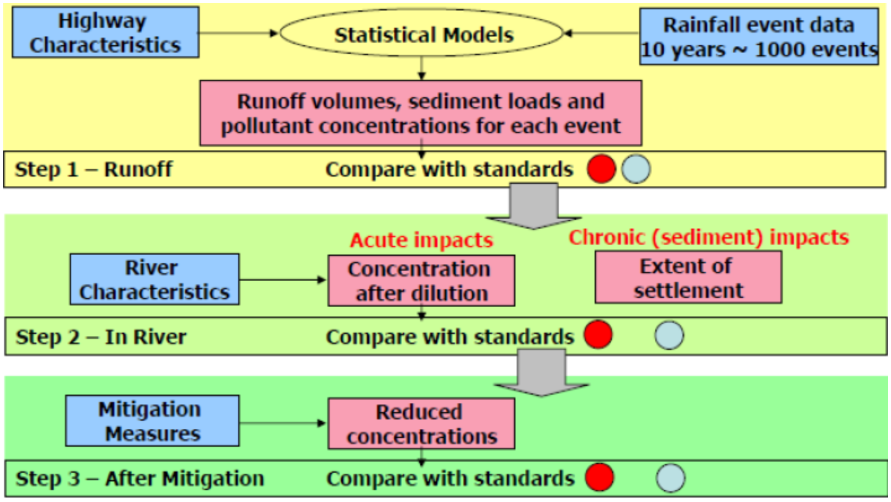

Figure 2.1. HAWRAT methodological scheme (Highways Agency, 2008)

The runoff pollution model incorporated in HAWRAT was developed based on a dataset of 24 highway sites across England with traffic density ranging from 11000 – 159000 vehicles/day (Moy et al., 2003 and Crabtree et al., 2008). HAWRAT has limitations in its application in the following scenarios: (i) urban highways; (ii) highways with traffic densities outside the 11000-159000 vehicles/day range[3]; (iii) highways discharging to receiving watercourse that are tidal and/or saline.

Step 1 uses statistical models of monitoring data to determine pollutant concentrations in raw road runoff prior to any treatment or dilution in the receiving watercourse. The average of the Event Mean Concentrations (EMC) are used to calculate Site Mean Concentration (SMC). EMCs are calculated taking into account the following multiple linear regression:

[2] Currently called Highways England Water Risk Assessment Tool.

[3] Anyhow for roads bellow this range, a maximum pollutant concentration may be obtained.

$$\log_{10}EMC = PC + CRC + AADTC + MC - \gamma_1 \times MHI + \gamma_2 \times ADP$$

where:

PC is a pollutant constant (-);

CRC is a Climate region constant (-);

AADTC is a constant related to the annual average daily traffic (-);

MC is the month constant (-);

MHI is the maximum hourly precipitation (mm);

ADP is the antecedent dry period (hours);

γ_1 and γ_2 are regression coefficients

All constants and coefficients are presented in Table 2.2.

CRC is defined for the UK and depends on the climate. The country is divided in 4 areas according to the following classification in climate regions: i) cold/wet; ii) cold/dry; iii) warm/dry and iv) warm/wet.

Table 2.2. Constants used in HAWRAT (Dempsey and Song, 2008)

			EMC constants			
			Total Copper	**Total Zinc**	**Total Cadmium**	**TSS**
PC			1.394	1.91	-0.832	2.1
CRC	Site	Cold/Dry	0	0	0	0
		Cold/Wet	0.042	0	0	-0.217
		Warm/Dry	0.144	0	0	-0.248
		Warm/Wet	0.089	0	0	-0.163
AADTC	Traffic	AADT<50000	0	0	0	0
		50000=<AADT<100000	0.018	0.045	0.093	0
		AADT>=100000	0.512	0.502	0.379	0
MC	Months	1	0.402	0.662	0.773	0.535
		2	0.568	0.699	0.565	0.443
		3	0.526	0.704	0.625	0.324
		4	0.427	0.504	0.374	0.193
		5	0.559	0.716	0.579	0.288
		6	0.425	0.32	0.241	0.283
		7	0.258	0.27	0.064	-0.148
		8	-0.064	-0.154	-0.216	-0.108
		9	0.065	-0.098	-0.067	-0.101
		10	0	0	0	0
		11	-0.028	0.068	0.05	0.022
		12	0.085	0.231	0.181	0.491
γ_1/γ_2	Extra	γ_1 (MHI)	0	0.022	0	0.065
		γ_2 (ADP)*	0	0	0	0

* This value is only zero for the pollutants considered in the present analysis (in the manual, this value is different from zero just for dissolved copper).

HAWRAT was implemented in an Excel spreadsheet and macros. The user selects and inputs the information related to the highway site under analysis. The equations and constants are embedded in the Excel file allowing its application within the UK context.

2.4 Multiple linear regression (Kayhanian et al., California, USA, 2007)

Kayhanian *et al*. (2007) proposed a multiple linear regression (MLR) to predict EMCs. This regression was established with the following specific objectives: (i) providing a statistical summary of highway runoff quality in California (USA); (ii) discussing the impact of selected independent event and site characteristics parameters on highway runoff constituent EMCs and (iii) evaluating the application of the MLR models as predictive tools to estimate the constituent EMCs.

Stormwater runoff data used in Kayhanian *et al*. (2007) were from 34 highway sites in California, covering a wide range of annual average daily traffic levels and environmental conditions. These data was obtained with up to 8 storm events at each highway site during wet seasons, during a period from 2000 to 2003. Other characteristics that were identified in each site, are: surrounding land use, catchment area, impervious fraction, latitude and longitude and AADT.

The MLR equation established by Kayhanian *et al*. (2007) is the following:

$$\ln(\mathrm{EMC}) = \beta_0 + a \times \ln(\mathrm{TER}) + b \times \ln(\mathrm{ADP}) + c \times \sqrt[3]{\mathrm{CSR}} + d \times \ln(\mathrm{DA}) + e \times (\mathrm{AADT} \times 10^6)$$

where:

TER is the total event rainfall (mm);

ADP is the antecedent dry period (days);

CSR is the cumulative seasonal rainfall (mm);

DA is the drainage area (ha);

AADT is the annual average daily traffic (veh/day).

The equation was calibrated for several pollutants. Regression coefficients β_0, a, b, c, d and e are presented in Table 2.3.

Table 2.3. Regression coefficients

Constituent		β_0	a	b	c	d	e
Aggregates	Total Suspended Solids	4.28	0.124	0.102	0.099	—	4.934
	Total Dissolved Solids	4.73	0.309	0.126	0.05	—	2.582
	Dissolved Organic Carbon	4.11	0.404	0.123	0.129	—	—
	Total Organic Carbon	4.11	0.404	0.123	0.129	—	—
Metals (total)	Copper	2.9	0.161	0.163	0.079	—	6.823
	Lead	2.72	—	—	0.102	—	9.65
	Nickel	2.51	0.196	0.141	0.075	0.155	1.013
	Zinc	4.83	0.227	0.143	0.084	—	6.747
Metals (dissolved)	Copper	2.92	0.29	0.185	0.102	—	3.679
	Lead	2.04	0.248	—	0.101	—	0.007
	Nickel	2.73	0.27	0.068	0.107	0.094	—
	Zinc	4.74	0.343	0.164	0.112	—	1.676
Nutrients	NO_3-N	1.3	0.417	0.092	0.09	—	2.87
	P. total	1.2	0.143	0.128	0.051	—	0.9
	Total Kjeldahl Nitrogen	1.7	0.343	0.102	0.128	—	1.535

2.5 Stochastic Empirical Loading and Dilution Model (SELDM, USA, 2013)

The Stochastic Empirical Loading and Dilution Model (SELDM) was developed by the US Federal Highway Administration and provides predictions of EMCs, flow and pollutant loads in stormwater from a highway site. Using input information based on site and catchment characteristics, rainfall, stormflow, water quality and the performance of mitigation measures, this tool generates statistical distributions of runoff quality in highway runoff and receiving water bodies. In the present work only the first component was of interest. SELDM is based on a highway runoff database which contains data from over 4000 storm events, using a Monte Carlo analysis to generate the output results such as EMCs (Gardiner *et al.*, 2016).

Note that SELDM has also a stochastic module to assess the potential benefits of the implementation of stormwater control (not relevant for the objective of this report). SELDM is open access software that can be downloaded.

SELDM is not calibrated by changing values of input variables to match a historical record of values. Instead, SELDM's input variables are based on site characteristics and representative statistics for each hydrological variable. A mass balance is used to estimate the concentrations and loads of water quality constituents in receiving waters, (Granato, 2013).

Storm events are defined as statistically independent events characterized by a volume, intensity, duration and time between midpoints of successive storms for the purposes of planning, analysis, and sampling efforts (Driscoll, 1990; Granato, 2013).

The fact that SELDM was designed to predict road runoff pollution in US areas represents a limitation to its use abroad. The model defines "Ecoregions" where the parameters are automatically chosen accordingly to the USA context. Nevertheless, the tool might be used elsewhere if the needed input information of weather conditions is known and inserted by the operator.

In order to use SELDM, the input layout is a sequence of graphical user interface (GUI). In total, 14 forms need to be completed with several type of information such as the highway characteristics or the precipitation statistics. When the mandatory inputs are filled in, the user is able to run the tool. As for road runoff pollution, only two from the 14 outputs are of interest to the objective of PROPER WP1, namely: (i) Precipitation event output file and (ii) Highway runoff quality output file.

The Highway Runoff Database (HRDB) developed by the United States Geological Survey is designed as a data warehouse to store information from highway runoff monitoring studies and as a pre-processor for highway runoff data for use in SELDM. Available highway runoff data provide the basis for defining runoff quality and quantity at monitored sites and predicting runoff quality and quantity at unmonitored sites. HRDB includes data from 2650 storms, 39713 EMCs measurements of more than 100 water quality constituents monitored at 103 sites in USA (Granato and Cazenas, 2009). This data has been monitored from year 1975 up to year 1985, therefore includes a wide range of vehicle, precipitation events and operational characteristics. It can also be seen as outdated since the characteristics of car, engines, fuels, etc. are no longer the same.

3 | Summary of the monitoring data

A total of 22 case studies were gathered from 7 different countries, namely, Norway, England, Switzerland, France, Ireland, The Netherlands and Portugal. The case studies location is presented in Figure 3.1, where the dots represent the road sites the map of Europe shows the annual average precipitation ranges.

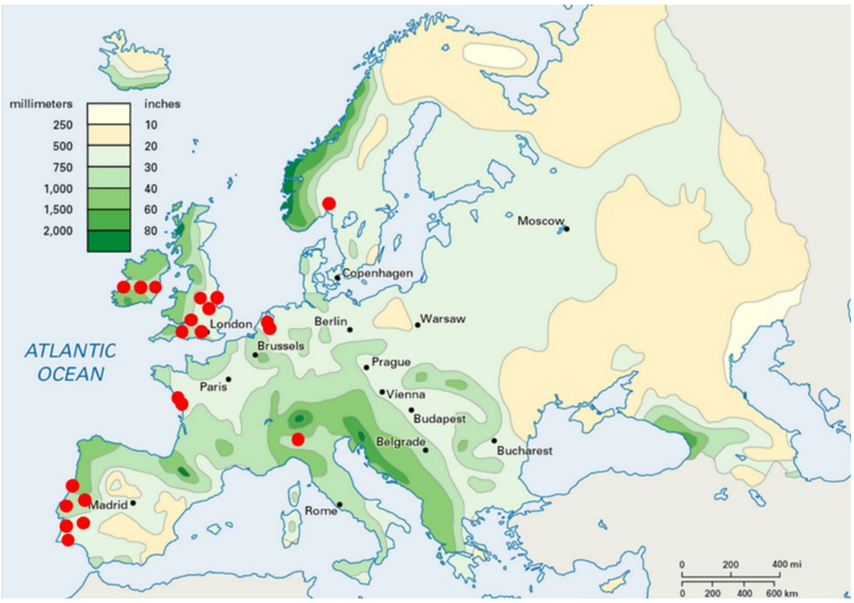

Figure 3.1. Europe precipitation map with the roads under study, case studies are identified with red dots

In PROPER report D1.3 the sites were characterized in detail. The 22 roads are located in regions with annual precipitation values ranging from 500 to 2000 mm, which represent most of the European territory. Data from France stand for the same road and site with two different pavements (porous and conventional asphalt) and were considered as 2 different case studies.

These 22 road sites cover a wide range of conditions and their main characteristics are presented in Table 3.1. The drainage areas (DA) range from 290 m^2 to 58680 m^2; the annual precipitation (P_{annual}) from 510 mm to 843 mm and the Annual Average Daily Traffic (AADT) from 2918 up to 78000. For these 3 variables, the lowest value concern to Portuguese roads and the highest to English roads. The lowest impervious fraction of a monitored road catchment also regards a Portuguese road (A1), with around 41% of impervious area. The two countries providing more road sites are Portugal and England. In this sample, Portugal 6 sites overall include the widest variety of DA, IF, P_{annual} and AADT.

Table 3.1. Characterization of the road sites.

Code	Country	Road/Highway designation	Drainage Area (DA) (m^2)	Impervious fraction (IF) (0-1)	Annual precipitation (P_{annual})* (mm)	Annual average daily traffic (AADT) (no. vehicles)
P1	Portugal	A 1	22800	0.41	646	27746
P2		A 2	1287	1	528	16344
P3		A 6	5580	1	744	2918
P4		A 22	15422	0.85	518	24000
P5		A 25	287.5	1	1014	15673
P6		IP 6	7280	1	709	6539
N1	Netherlands	A 27 - pervious	48590	0.5	776	63000
N2		A 27 - impervious	30510	1	776	63000
N3	Norway	E 6	22000	1	834	42000
F1	France	A 11 - pervious	3200	1	786	24103
F2		A 11 - impervious	3200	0.5	786	24103
I1	Ireland	M 7 - Kildare	14184	1	731	27500
I2		M 7 - Monasterevin	11368	1	731	27500
I3		M 7 - Portlaoise	9600	1	731	27500
E1	England	M 4 - Brinkworth	8755	1	745	70000
E2		M 4 - River Ray	4348	1	745	35000
E3		M 40	58680	1	615	78000
E4		A 417	20232	1	843	24000
E5		A 34 - Gallos Brook	2760	1	660	64000
E6		A 34 - River Enborne	19425	0.5	635	36000
S1	Switzerland	A12 Bümplizstrasse	42084	1	986	38985
S2		A1 Gabelbach	12200	1	986	39500

*P_{annual} information was collected from national databases: snirh.apambiente.pt/; www.climatedata.eu; fr.climate-data.org; weather-and-climate.com; www.metoffice.gov.uk; www.meteosuisse.admin.ch (different years were considered)

Table 3.2 presents the physical variables that serve as input to the 4 models. The identification of each of the highways was made through the same code as used in Table 3.1 (using a letter and sequential numbering for each country's data).

Table 3.2. Physical characteristics of road used as inputs in the tools

Highways	Climate Region (HAWRAT)	DA (m^2)	Drainage lengh (m)	Slope (%)	IF (0-1)	P_{annual} (mm)	AR (mm)	AADT (no. vehicles)
P1	Warm/Wet	22800	814	2.95	0.41	646	7.80	27746
P2	Warm/Wet	1287	117	7.70$^{(c)}$	1.0	528	6.00	16344
P3	Warm/Wet	5580	465	3.00$^{(c)}$	1.0	744	5.50	2918
P4	Warm/Wet	15422	612	3.40$^{(c)}$	0.85	518	7.00	24000
P5	Warm/Wet	287.5	25	2.50	1.0	1014	6.00	15673

Highways	Climate Region (HAWRAT)	DA (m^2)	Drainage lengh (m)	Slope (%)	IF (0-1)	P_{annual} (mm)	AR (mm)	AADT (no. vehicles)
P6	Warm/Wet	7280	520	3.30[c]	1.0	709	6.00	6539
N1	Warm/Dry	48590	1600	0.20[c]	0.5[d]	776	3.67	63000
N2	Warm/Dry	30510	2700	0.20[c]	1.0	776	6.00	63000
N3	Cold/Dry	22000	1630[b]	3.40[c]	1.0	834[e]	2.50	42000
F1	Warm/Wet	3200	275	2.50	1.0	786	9.00	24103
F2	Warm/Wet	3200	275	2.50	0.5[d]	786	9.00	24103
I1	Cold/Wet	14184	1200	0.94	1.0	731	3.80	27500
I2	Cold/Wet	11368	480	0.50	1.0	731	3.80	27500
I3	Cold/Wet	9600	800	0.50	1.0	731	3.80	27500
E1	Warm/Wet	8755	724	1.10[c]	1.0	745	2.08	70000
E2	Warm/Wet	4348.05[a]	303	0.66[c]	1.0	745	1.48	35000
E3	Warm/Dry	58680	1800	2.40[c]	1.0	615	3.27	78000
E4	Warm/Wet	20232	735	3.10[c]	1.0	843	1.55	24000
E5	Warm/Wet	2760	250	0.80[c]	1.0	660	1.19	64000
E6	Warm/Wet	19425	1050	0.19[c]	0.5[d]	635	5.90	36000
S1	Warm/Wet	42084	1625	0.43[c]	1.0	1074	2.15	38985
S2	Warm/Wet	122000	4300	1.67[c]	1.0	1100	2.60	39467

The monitored data is available in: Barbosa and Fernandes, 2012; Leitão *et al.,* 2005; Antunes, 2014; Barbosa et al., 2011; Brongers, 2011a; Brongers, 2011b; Vollertsen *et al.,* 2007; Mufleh et al., 2010; Higgins, 2007; Moy and Crabtree, 2002a; Moy and Crabtree, 2002b; Moy and Crabtree, 2002c; Moy and Crabtree, 2002d; Moy and Crabtree, 2002e; Moy and Crabtree, 2002f.

The Intensity-Duration-Frequency (IDF) curves used as AR auxiliary calculations are available at: Brandão et al., 2001; Korving et al., 2009; http://eklima.met.no; EDF-DTG and Cemagref, 1993 and https://www.met.ie.

[a] Estimated drainage area by multiplying the length by the section width

[b] Estimated drainage length by dividing the available area by the width consulted in Google Earth Pro

[c] Estimated slopes through the Google Earth Pro function, elevation profile

[d] Assumed impervious fraction

[e] Assumed P_{annual}

Not all the information regarding these 22 case studies was available in the reports from where data was taken out, therefore some assumptions were made.

A climate region was assigned to each case study according to the specification of HAWRAT. For this, the red lines that divide each climatic region in HAWRAT (only for United Kingdom) were extended to whole Europe.

The drainage area and length were known for most of the cases. When the first variable was not referred, the value was estimated by multiplying the length of the road by its width. For the case of the drainage length, when unknown, it was calculated through Google Earth. The same software also supported the estimation of the missing slopes through the elevation profile function (these calculations are referred in the table 1.3 notes).

The impermeable fraction for roads N1, F2 and I6 was assumed as being of 0.5 because the reports with the study characterization only inform that the highways have permeable asphalt.

The annual precipitation was calculated through the average of annual precipitation data of each site. The only highway for which annual precipitation was calculated based on the hourly precipitation data was N3 due to the lack of annual precipitation data.

To calculate Average Rainfall (AR for PREQUALE), Intensity-Duration-Frequency (IDF) curves[4] were consulted. For some cases, these curves were not available and AR was calculated as the average of the precipitation volume for the events identified in the precipitation time series.

[4] The Intensity-Duration-Frequency (IDF) curves used as auxiliary calculations (for AR*, cf.* Table 3.2) and are available at: Brandão et al., 2001; Korving et al., 2009; http://eklima.met.no; EDF-DTG and Cemagref, 1993 and https://www.met.ie.

4 | Results

4.1 Methodology

As described in section 3, the 4 tools require different processes for their implementation. SELDM has a graphical interface and all calculations are performed in the software. PREQUALE uses a simple equation to directly calculate the SMC. HAWRAT and the equations proposed in Kayhanian et al. (2007) were implemented in an excel spreadsheet. Note that since HAWRAT has a spreadsheet designed to work within the UK context, to use it for other sites - like what was done for this study – required to embed HAWRAT equations in a created excel spreadsheet.

For each case study presented in Table 3.1, Site Mean Concentrations (SMC) were calculated by averaging the Event Mean Concentrations (EMC), both monitored and modelled. Looking at the available monitoring data and the list of pollutants predicted by the 4 tools, the following pollutants were selected for the assessment of the tools: total suspended solids, copper, zinc, lead and cadmium. These pollutants are included in the list of key pollutants in road runoff referred in report D1.1 of PROPER project.

More details of methodology and approaches used to test each of the models are presented in the next paragraphs.

PREQUALE

PREQUALE is a multiparametric equation that calculates SCM. The following input variables must be known:

(i) Drainage Area - given for each road or was obtained in google earth
(ii) Impervious fraction - given for each road or assumed to be impervious
(iii) Average annual rainfall volume with the same duration as the time of concentration of the basin
(iv) Annual average precipitation – obtained for each site

HAWRAT

To be able to apply HAWRAT, hourly precipitation time series were used and the following parameters were taken from the road site characterisation or calculated:

(i) PC is the pollutant constant - given by the developer and dependent of the pollutant
(ii) CRC is the Climate region constant - given by the developer and related the climate region; CRC is defined for the UK and depends on the climate. The country is divided in 4 areas according to the climate regions, cold/wet, cold/dry, warm/dry and warm/wet. For its use outside UK, the division lines were extended as proposed in the manual of the tool
(iii) AADTC is the constant related to to the annual average daily traffic - given for each road
(iv) MC is the month constant - related to the month of the rainfall event

(v) MHI is the maximum hourly precipitation - given for each event (from the hourly precipitation time series)
(vi) ADP is the antecedent dry period - given for each event (from the hourly precipitation time series)

Kayhanian et al. (2007)

The model proposed in Kayhanian *et al.* (2007) calculates the event mean concentration for each pollutant. The hourly precipitation time series was used to obtain the following equation input parameters:

(i) TER is the total event rainfall - calculated from the hourly precipitation time series for each event
(ii) ADP is the antecedent dry period - calculated from the hourly precipitation time series for each event
(iii) CSR is the cumulative seasonal rainfall - calculated as the average for each season
(iv) DA is the drainage area - given for each road or was obtained in google earth
(v) AADT is the annual average daily traffic - given for each road

SELDM

SELDM is the most demanding tool in terms of input data. The graphical user interface has 14 forms requesting different input information. The most important variables related to the road runoff are included in 2 forms, and are the following:

(i) Highway physical characteristics
(ii) Ecoregion (when the site under study is in USA)
(iii) Precipitation statistics (when the ecoregion is settled the form is almost automatically filled for USA sites. For the present study, it was needed to calculate this variable outside the tool)
(iv) Runoff coefficient statistics
(v) Highway runoff quality statistics

PREQUALE equation provides directly the SMC. For the other 3 tools, a series of event mean concentrations were calculated and then averaged to obtain the SMC for each of the 22 case studies.

4.2 Comparison of the predictions

The comparison between the Site Mean Concentrations predicted by the 4 models and the Site Mean Concentrations resulting from monitoring work is presented in Figure 4.1, for the 22 roads and the 5 pollutants selected as key parameters in this study.

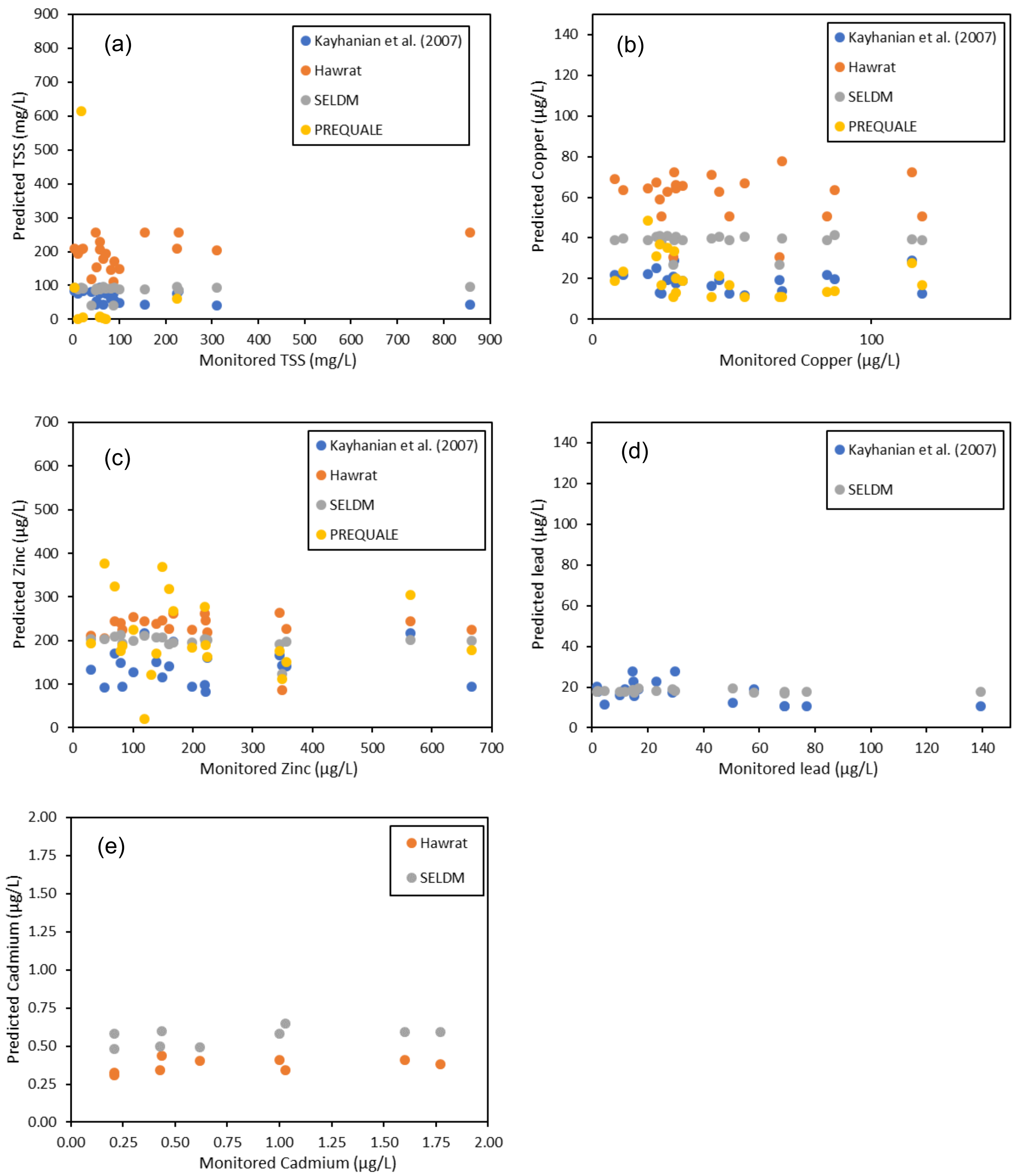

Figure 4.1. Comparison SMC monitored and predicted (a) TSS; (b) copper; (c) zinc; (d) lead and (e) cadmium

The comparison between monitored and predicted site mean concentrations clearly shows that none of the tools is able to predict the concentration of pollutants or to capture the trend of the monitoring data. Comparing the overall set of predicted values for the 22 roads, it is seen that they show little variability, whereas monitored data do show such expected variability. This means that the 4 tools under evaluation do not have much sensitivity to the input values. This qualitative and visual analysis was followed by a quantitative assessment by calculating the coefficients of determination (R^2) defined as $R^2=$

$$\left[\frac{\sum_{i=1}^{n}(O_i - \bar{O})(P_i - \bar{P})}{\sqrt{\sum_{i=1}^{n}(O_i - \bar{O})^2} \times \sqrt{\sum_{i=1}^{n}(P_i - \bar{P})^2}}\right]^2$$

where n is the number of SMCs under evaluation, O_i is the monitored value; P_i is the predicted value and the overbar means averaged values.

Table 4.1 presents the error indices associated to the predictions depicted in Figure 4.1. As the R^2 are relatively low (ranging between 0.0004 and 0.2890) it is confirmed the empirical observation that no linear relationship exists between the monitored and the predicted values.

Table 4.1. Error indices

		R^2
TSS	HAWRAT	0.1682
	Kayhanian	0.1468
	SELDM	0.1803
Copper	PREQUALE	0.1219
	HAWRAT	0.0209
	Kayhanian	0.0019
	SELDM	0.0004
Zinc	PREQUALE	0.0087
	HAWRAT	0.0111
	Kayhanian	0.0072
	SELDM	0.0685
Lead	Kayhanian	0.2890
	SELDM	0.0575
Cadmium	HAWRAT	0.0127
	SELDM	0.0039

4.3 Critical review of the 4 tools

The application of the tools was done following a period of study of each of them, and efforts regarding understanding their context of use, characteristics of input data and type of outputs given. For someone not acquainted to the tools, the only one that is straightforward and simple to be implemented is the PREQUALE equation.

After having achieved all the steps of fully understanding the models; having selected the roads, calculated the additional parameters needed for each case, as input to the different 4 tools (*cf.* Table 3.2), the calculation of the SMC for all was successfully undertaken.

Almost all data is easily available for the application of PREQUALE. For this tool, only the Average Rainfall needs further calculation and a calibrated IDF curve for the site.

The application of HAWRAT is simple for sites located in the UK. This software has included the data for the meteorological stations in the UK. For other countries outside the UK, HAWRAT is more difficult to apply and an hourly precipitation time series is needed in order to calculate all parameters and obtain the pollutant concentrations. In the present analysis, it was observed that HAWRAT is quite sensitive to the month of the rainfall event. Therefore, its use outside UK is more difficult, specially to climate regions different than the four ones defined for the UK.

Similar problems were faced during the implementation of SELDM. In this case, its use outside USA is complicated because, to do so, several precipitation statistics are needed.

The characteristics of road runoff pollutants have been studied by several authors in different countries, as showed in the literature. Published work present typical ranges of concentrations commonly found in road runoff have been produced. There are variations in monitoring results regarding a same case study and between events. Table 4.2 presents the monitoring results obtained in two different years for A1 Highway, in Portugal. The work was done by the same team, by using the same equipment and methodology; the analyses have been done by different laboratories. The type of events (rainfall volume, intensity and duration) have, of course, been different. The differences observed in the range of values for is a practical example confirming that, even for a given site with consistent monitoring information, the SMC can only be approached and never known as an exact value.

Table 4.2. Comparison of monitoring results (range of concentrations) for two different years, for the A1 highway (Portugal) (Barbosa et al., 2011)

	A1 AADT = 30299 Monit. 2002	**A1** AADT = 27746 Monit. 2009
Total samples*	5–93	37–73
Total events	6	11
pH	6.3 – 7.4	5.8 – 7.2
Conductivity (μS/cm)	124 – 357	58.0 – 288.0
TSS (mg/l)	10.0 – 872	0.3 – 350.0
Fe (mg/l)	0.086 – 3.030	0 – 7.192
Zn (μg/l)	62 – 736	0 – 834
Cu (μg/l)	27 – 76	0 – 51
Pb (μg/l)	2 – 58	2 – 58
Cd (μg/l)	< 0.5	0.09–0.32
Oil & Grease (mg/l)	3.2 – 40	0 – 16.0

* Not all parameters have been determined in all samples.

It seems clear that we cannot establish a “strict” and constant Site Mean Concentration (SMC) for any specific road site because variables such as rainfall volume or the antecedent dry period can have great variation between events leading to rather different pollutant concentrations. Not forgetting variations in the traffic volume, new engines and technological development, new materials used in road construction and road furniture, surrounding soil use, among many other variables. This means that if needed to know with accuracy the SMC for a given site, monitoring work must be done periodically.

Driscoll *et al.* (1990) has approached this subject, by stating that highway and vehicle changes over decades can results in changes in the concentrations (e.g. changes in lead content of motor vehicle fuels).

Table 4.3 presents a summary of site mean concentrations regarding the 5 pollutants selected for this evaluation, and for roads in different countries, as presented in several references. It is also observed that the monitoring results as old as 1975 should not be able to represent present conditions.

Table 4.3. Site mean concentrations found in the literature

Pollutant	AADT	TSS (mg/l)	Zinc (ug/l)	Copper (ug/l)	Lead (ug/l)	Cd (ug/l)	Observations
Current study	3000-78000	4 - 856	29 - 667	8 - 118	2 - 139	0.2 - 8.7	Based on 22 roads across Europe, with monitoring data from 1995 to 2015
Barbosa et al. (2011)	3000-43000	7 - 225	76 - 346	8 - 72	2 - 44	-	Monitoring data from 10 highways in Portugal from 1996 to 2010
Driscoll et al. (1990)	>30000	142	329	54	400	-	Based on field measurements taken between 1975-1985. Data from 993 separate highway runoff events at 31 sites in 11 states in the USA
	<30000	41	80	22	80	-	
Trafikverket (2011)	10000-15000	75	100	35	20	0.5	
	15000-30000	100	150	45	25	0.5	
	>30000	1000	250	60	30	0.5	
Drapper et al. (2000)	6000-50000	60-1350	150-185	30-340	80-620	-	Based on 21 sampling sites in southeast Queensland, Australia
Barret et al. (1995)	9000-60000	19-131	22-208	7-34	7-50	-	Based on 3 highways in Austin, Texas, USA. Field measurement were obtained from 1993 to 1995
Crabtree et al. (2006)	23600-83500	115	140	41	23	-	Based on 6 highways located in the UK between 1997 and 2002 (10 events at 6 sites)

Summing up, it is not expected that a single deterministic tool, that has been calibrated and validated for a given site, region or country is able to be widely used.

The prediction of pollutant concentrations in road runoff is not straightforward. This complexity is observed in the multiple predicting models that are available in the literature and in the choice for the input data that is required.

5 | Final remarks

Knowledge of the characteristics of road runoff pollution being discharged from roads is crucial for the evaluation of its potential impacts on water bodies and related ecosystems, and to inform decisions on the need to construct treatment systems for impacts mitigation. The most precise method to characterise road runoff pollutant concentrations and loads is to carry out road runoff monitoring programs, including automatic sampling of rainfall and runoff, ecological and physico-chemical analysis of samples and calculation of the Event Mean Concentrations (EMC) / Site Mean Concentrations (SMC) and pollutants loads. It is generally accepted that at least 10 stormwater events from independent rainfall events must be monitored to calculate a robust SMC for a given location. Monitoring work requires considerable human, and material resources and are subject to uncontrolled variables, such as equipment damage or loss; absence of (appropriate) rainfall events, etc.

Therefore, pollutant concentration/load prediction tools could be an important method to enable protection of the environment and water resources, as well as manage and reduce road runoff pollution discharges. The foundation of any consistent and sound prediction tool is a substantial road runoff monitoring database from sites with different characteristics.

The scope and objectives of WP1 activity within the PROPER project was to pursue the possibility of finding one or more tools for road runoff prediction that could be widely used across Europe. Among these tools, two have been appointed by the CEDR call text, HAWRAT (developed for the UK) and SELDM (developed for the USA). The work done was wider and more comprehensive having taken four different tools and using monitoring data from 22 different roads in Europe, from 7 different countries, namely, from Portugal, France, The Netherlands, Switzerland, England, Ireland and Norway. The other 2 additional tools were PREQUALE (developed for Portugal) and an equation from Kayhanian et al (develop for California, USA).

The overall results showed that none of the 4 tested tools are able to predict the road runoff pollutant concentrations. It is understood that the work done within WP1 from the PROPER project is very valuable in terms of conclusions and guidelines for the future practice and approaches to prediction of road runoff pollutant concentrations.

No tool will be able to consistently predict road runoff pollutants concentrations outside the site/region where it was calibrated. Even for a given location when thorough values are for some reason needed, periodic monitoring work must be done so that the SMC can be checked and corrected. Therefore, it is not recommended to support road runoff pollution control decisions based on road runoff prediction tools that were not established for that same site/region/country or that are outdated.

In fact, for the purpose of water resources management and mitigation of impacts, different alternative approaches should be discussed. Approaches based on the need or not to protect water resources[5] and then use an average estimation of SMC that can guide the implementation of treatment systems and other strategies for impact reduction.

Furthermore, most of the European countries have already a consolidated roads network being relevant to provide tools for understanding when and to which extent some of these infrastructures are responsible for impacting natural resources (water and soil). Providing guidelines to control and minimise impacts is also important as they can be used by operation roads and also in case of new projects. A consolidated roads' network will have rehabilitation works that have specific and temporary impacts that must be tackled.

PROPER provides information regarding surface and groundwater bodies' vulnerability to receiving road runoff pollution in the deliverables from WP2 (e.g. Revitt et al. 2018). The deliverables from WP3 and WP4 are contributing to providing guidelines for sustainable measures to minimise impacts from roads operation and construction.

Based in all the work done within WP1 and the experience of the authors, it is understood that the specific site/regional characteristics of climate and water bodies (among others variables, such as countries own administrative and governance practices) it would make sense that each country establishes a simple objective and straightforward method to deal with road runoff pollution and control its impacts in the environment. The results from this report and other tasks in PROPER can support and inspire such strategies.

[5] For instance, a simple approach considering 3 frameworks could be useful: i) need to prevent any kind of deterioration of the water quality (or soil, etc.); ii) need to minimize impacts because the road has high traffic volume and/or discharge can impact water systems of importance/specific uses/ specific protection legislation; and iii) no need to control road runoff discharges.

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